Heiko Johannsen (Editor)

FIMCAR

Frontal Impact and Compatibility Assessment Research

SEVENTH FRAMEWORK PROGRAMME

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FORWORD

The present book summarises the results of the European project FIMCAR. The FIMCAR project was co-funded by the European Commission within the 7th Framework Programme (Grant Agreement no. 234216) and was conducted from October 2009 to September 2012.

This book is composed of the public deliverables of the project that have been subjected to an additional review to improve readability and avoid misunderstanding. The general content was not modified except for Section VI (Off-set Test Procedure: Updated Protocol). Several project results of the off-set test procedure work package were not reported in the original deliverable D2.2. Therefore it appeared sensible to update the document with information that was originally not reported. Furthermore the original Deliverable D1.3 (Section XV) was supplemented by parts of a confidential deliverable in order to make it complete. Finally Section IV FIMCAR Models was added because the simulation models were used in several deliverables without a public reference for the models.

The sections of the book are not following the project structure nor the date of the original publication of the deliverables. The resulting document has the following sections

- I Summary Report (origin: Final Technical Report): gives a general overview of the project and its results
- II Accident Analysis (origin D1.1): describes the accident data analysed to obtain an overview of frontal impact issues in a modern fleet and the results of this study
- III Car-to-Car Tests (origin D6.1): describes the car-to-car tests performed including their results
- IV FIMCAR Car Models: describes the modelling approach for the FIMCAR models including their validation basis and some of the results obtained with the models (this section was not published before in a public deliverable)
- V Off-set Test Procedure: Review and Metric Development (origin D2.1): describes the initial analysis of off-set assessment procedures and the beginning of the PDB metric development
- VI Off-set Test Procedure: Updated Protocol (origin D2.2): describes the final FIMCAR off-set assessment protocol including the rationales for selection and further improvements of the PDB assessment protocol (this section was supplemented by additional results in comparison to D2.2)
- VII Full-width Test Procedure: Review and Metric Development (origin D3.1): describes the initial analysis of full-frontal assessment procedures and the beginning of FWRB and FWDB metric development
- VIII Full-width Test Procedure: Updated Protocol (origin D3.2): describes the final FIMCAR Full-width Assessment Procedure including the rationales for selection
- IX MDB Test Procedure: Initial Protocol (origin D4.1): describes the initial MDB test protocol as no suitable protocol could be used by FIMCAR
- X MDB Test Procedure: Test and Simulation Results (origin D4.2/D4.3): describes all MPDB tests including their relevant results that were available for FIMCAR
- XI FIMCAR Final Assessment Approach (origin D6.3): describes the FIMCAR evaluation process for the selection of the assessment procedures that form the FIMCAR Assessment Approach, the reasons for selecting the assessment procedure and the FIMCAR Assessment Approach itself

- XII Influence on Other Impact Types (origin D6.4): describes the expected influence that the different assessment procedure may have on other impact types that car-to-car frontal impact and car-to-object frontal impact
- XIII Cost Benefit Analysis (origin D1.2): describes benefit analysis performed within FIMCAR to estimate the break even costs for additional introduction of any full-width test assessment procedure and replacing the current ODB off-set test with the PDB procedure
- XIV Potential of Simulation Tools (origin D5.5): describes a possible approach towards frontal impact compatibility by means of Virtual Testing
- XV Fleet Studies (origin D1.3): describes the process for the development of Multi Body Fleet Models and the implications of the different assessment objectives calculated with these models (this section was supplemented by a description of the modelling process for the Multi Body Models in comparison to the original D1.3)

The FIMCAR Consortium was composed of the following 18 European organisation: Technische Universität Berlin, Bundesanstalt für Straßenwesen. Chalmers tekniska hoegskola AB (with Statens väg- och transportforskningsinstitut as a third party), Centro Recerche Fiat S.C.p.A., Daimler AG, FIAT Group Automobiles Spa, Humanetics GmbH, IAT Ingenieurgesellschaft für Automobiltechnik mbH, IDIADA Automotive Technology SA, Adam Opel GmbH, Peugeot Citroën Automobiles SA, Renault s.a.s, TNO, TRL Limited, UTAC, Volvo Car Corporation, Volkswagen AG, TÜV Rheinland TNO Automotive International BV. In addition to these organisations the project cooperated with external organisations, i.e., JMLIT, Nagoya University, JAMA, GRSP, GRSP Informal Group on Frontal Impact, Euro NCAP, ADAC, Kistler and Kia/Hyundai. All these partners and external organisations contributed directly or indirectly to the project results and the content of the book.

Although a large number of international organisations were involved in the discussions and interpretation of the project results, the content of the book may not be considered as the opinion of the European Commission or that of the individual partner organisations.

Heiko Johannsen

FIMCAR
I - Summary Report

FIMCAR
frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The goal of the FIMCAR (Frontal Impact and Compatibility Assessment Research) project was to propose a frontal impact assessment approach addressing self- and partner protection. Research strategies and priorities were based on earlier research programs and the FIMCAR accident data analysis looking at modern cars. The identified real world safety issues – such as structural interaction (especially under-/override), high acceleration loading of the occupant especially in large overlap accidents and insufficient horizontal and vertical load spreading were used for evaluating the different test candidates. In addition to the issues mentioned above, the FIMCAR accident analysis suggested that frontal force compartment integrity matching is less of an issue as originally expected.

FIMCAR developed a car-to-car test program that investigated the performance of vehicle structures. Results of the test program show that the presence of a lower load path contributes to a more robust performance of the vehicle. The rearward offset of a lower load path could be reviewed and used to quantify when a lower structure design can contribute to structural interaction in both frontal and side impact configurations.

In addition to the car crash test programme, numerical models of actual cars and barriers were developed and used. As car-to-car simulations with models of different car manufacturers are almost impossible because of confidentiality, Parametric Car Models (PCM) and Generic Car Models (GCM) were developed. Due to the parametric design of the PCMs it is possible to modify the models in an easy and fast way. The GCMs model virtual cars which represent an average real car of the respective category in a comparable way to the OEM models.

Within the FIMCAR project, different frontal impact test candidates were analysed regarding their potential for future frontal impact legislation. The research activities focused on car-to-car frontal impact. Test procedures were developed with both a crash test programme and numerical simulations.

This analysis resulted in the combination of the Full Width Deformable Barrier test (FWDB) with compatibility metrics and the existing Offset Deformable Barrier (ODB) as described in UN-ECE Regulation 94 with additional cabin integrity requirement as being proposed as the FIMCAR assessment approach. The advantages of the FWDB compared to the rigid wall are the more representative pulse and deformation pattern as well as the better assessment of load paths. The introduction of a (M)PDB without compatibility metrics (that FIMCAR was unable to deliver in time) was considered as not being appropriate.

The proposed frontal impact assessment approach addresses many of the issues identified by the FIMCAR consortium (impact alignment, high acceleration pulse loading, maintenance of compartment strength requirements, etc.) but not all frontal impact and compatibility issues could be addressed (load spreading).A benefit analysis estimated the benefit of the following three options: no change, introduction of full width test with compatibility assessment in addition to current ECE R94 and introduction of full width test with compatibility assessment and replacement of current ODB test by PDB test with load spreading metric. The comparison of calculated break even costs for option 2 with estimated costs for achieving the benefit from previous projects suggests a positive cost benefit ratio.

1 PROJECT CONTEXT AND MAIN OBJECTIVES

Crash compatibility has long been promoted as a key component in improving vehicle safety. Although compatibility has received worldwide attention for many years, no final assessment approach has been defined. FIMCAR (Frontal Impact and Compatibility Assessment Research) was a research project to address compatibility test procedures. The objective of the project was to answer the remaining open questions identified in earlier projects (such as understanding the advantages and disadvantages of force based metrics and barrier deformation based metrics, confirmation of specific compatibility issues like structural interaction, investigation of force matching) and to finalise the test procedures required to assess compatibility. Within the project, the research activities focused on car-to-car frontal impact accidents. However, other configurations such as lateral impact, car-to-HGV accidents etc. were also considered to ensure that changes made to cars to improve their compatibility in frontal impacts are not detrimental for other impact types.

Improvement of road safety is one of the major aims of road authorities, vehicle manufacturers, rescue organisations and research organisations amongst others. Measures to improve safety are historically divided into the area of active/primary safety (measures that help to avoid the occurrence of accidents) and passive/secondary safety (measures that help to reduce the consequences of accidents).

In the 27 EU member states, road fatalities are still a major cause of death although important safety improvements have reduced the number of killed people since 1990, see Figure 1.1. It should be noted that almost 50% of the 2008 road fatalities of the 27 EU member states were car occupants (Figure 1.2).

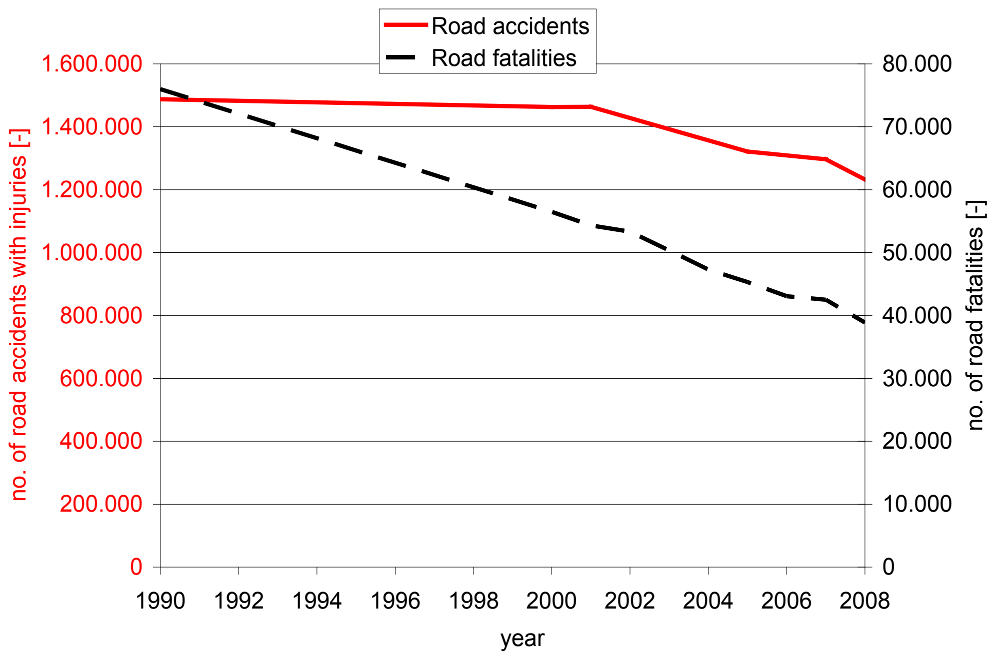


Figure 1.1: Development of road accidents causing injuries and road facilities in EU27 [Nicodème 2010].

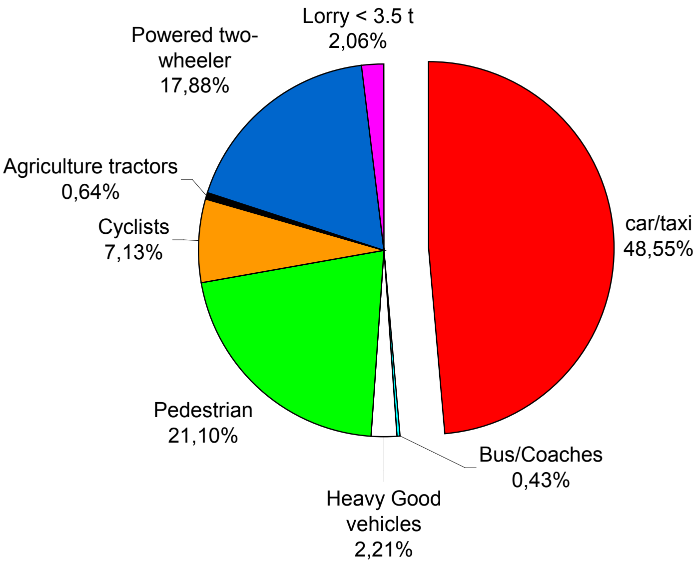


Figure 1.2: Distribution of road fatalities amongst road user categories 2008 in EU27 [Nicodème 2010].

The passive safety capabilities of cars are mainly assessed by crash tests. Currently different frontal test procedures are used in the different regions of the world. The most important test procedures are:

- Off-set test (40% of vehicle width) against a deformable element as currently used for homologation of cars in Europe (ECE R 94), the consumer information test program Euro NCAP, the US insurance company IIHS and others
- Full width test against rigid wall as currently used for homologation of cars in the US (FMVSS 208), the consumer information program US NCAP, homologation of cars in Japan and others

After the introduction of these tests, in particular the offset test, the safety performance of cars has improved in terms of test results. However it appears that cars rated good or excellent in the test programmes do not always perform well in car-to-car accidents. This behaviour was attributed as incompatibility between cars. It is this characteristic that was deemed important to assess and initiated different research activities.

Crash compatibility sometimes is a compromise between self and partner protection and it is important to not sacrifice one for the sake of the other. Compatibility will be used in the following document as a concept that is a combination of both self and partner protection. To break down the problem into specific issues, individual compatibility characteristics are identified that address only one aspect of frontal impacts i.e. self or partner protection. The goal of the project was then to identify the suite of tests that address all the important compatibility characteristics.

Compatibility is a global problem and research activities have taken place predominantly in the US, Japan and Europe. In all these areas, the activities are distributed between industry and government funded research activities. Different test methods have been investigated in the various regions but the global consensus in the IHRA compatibility working group [O'Reilly 2003] is that both an off-set and a full-width test are needed to fully assess compatibility and frontal protection performance. Each region has unique compatibility issues related to their respective traffic fleets, but similar strategies and approaches can be observed. A number of test alternatives are available for further development. An overview of the activities previous to FIMCAR is provided below.

European compatibility research has been undertaken at various research centres but the most significant activities have been coordinated by or reported to the EEVC WG15 (European Enhanced Vehicle Safety Committee Working Group 15 (Frontal Impact Compatibility)). This working group finished a mandate to investigate the test procedures needed to assess crash compatibility [Faerber 2007]. The working group results confirm that improving compatibility will have positive cost benefit results for Europe. Test methods to detect and assess compatibility were investigated with a focus on developing structural interaction assessments. The difficulty in defining an objective test approach for structural interaction was encountered by the working group. A list of open questions was developed, identifying the next steps needed to finalise compatibility test approaches.

One recent activity to note is the development of a moving deformable barrier test using a deformable element. This test method has been put forward by many researchers in Europe, USA and Japan as a long term solution to compatibility and has been reported previously [Summers 2002; Seyer 2003; Versmissen 2006].

Compatibility issues in the US are dominated by LTV/SUV (Light Truck Vehicles / Sport Utility Vehicles) impacts with smaller passenger cars. The most noteworthy development has been the industry voluntary commitment (coordinated through the Alliance of Automobile Manufacturers) [Auto Alliance 2003] to provide geometric overlapping of structures in frontal impacts, particularly in LTV to passenger car impacts. The commitment was initiated in 2003 and required 100% compliance for vehicle geometric designs by 2009. Parallel to the geometric requirement for structures, research into the parameters controlling compatibility has been investigated, including physical test requirements. One of the test methods under investigation is the high resolution load cell barrier that measures the force distribution over the vehicle front during a full width barrier test. This test approach is also under investigation by NHTSA and metrics such as the Average Height of Force (AHOF), Initial Stiffness (Ks), and Work Stiffness (Kw) have been derived from this type of test data and correlated to real world crashes [Summers 2005]. The US stakeholders have focussed their research efforts on the Full Width Rigid Barrier (FWRB) because it is the foundation of its frontal impact regulation. Most full width tests and analyses in the US have been for rigid barrier face.

Further work in frontal compatibility testing has been proposed in the Auto Alliance expert working group. The implementation of a moving deformable barrier for frontal crash testing had been investigated since the 1990's and has now been reviewed as method to control the frontal force levels in vehicles as well as addressing structural interaction. Further developments of this MDB have not been reported since 2008 although applications of an MDB for small overlap conditions has been under recent development [Saunders 2012].

The Japanese vehicle fleet, similar to Europe, is not characterised by a large LTV/SUV population that is found in the US. However, a particular difference in the Japanese and European vehicle fleet is the presence of so called mini cars in Japan that are designed to offer maximum internal space for a limited vehicle length. These cars normally have their bumper directly in front of the engine and do not incorporate any kind of crush can in the design because repair tests i.e. the RCAR (Research Council for Automobile Repair) bumper test, are not applicable. Legislative and consumer tests in Japan are based on the Full Width Rigid Barrier test and the recent adoption of the UNECE R94 offset test. The Japan Automobile Research Institute (JARI) as well as Honda has presented recent investigations of the use of load cell wall data as a method to assess compatibility. Alternative test approaches (with or without deformable honeycomb barriers) have been assessed and compared to car-to-car tests.

The Japanese automobile industry has investigated different testing or evaluation approaches. Toyota has researched the moving deformable barrier test for frontal impacts, partly in conjunction with the US industry research activities, and has developed a specific deformable element more complex than the EEVC or PDB barrier element. Analysis of load cell wall data from a full width test has also been proposed [Yonezawa 2011]

Previous research work on compatibility (e.g., EUCAR Compatibility project [Zobel 2001], EEVC WG 15 [Faerber 2007], VC-COMPAT [Edwards 2007] and other international and national research projects and working groups) has shown the main issues for improving compatibility are:

- Structural interaction
- Global force level matching
- Compartment strength and stability

The two most challenging compatibility issues were *structural interaction* and *global force matching.* Structural interaction describes how the contact forces are distributed across collision partners and the stability of the deforming structures. Good structural interaction is not commonly found in modern vehicles due the differences in vehicle sizes and crashworthiness designs. Poor structural interaction leads to phenomena such as over/underride or fork effect which in turn lead to undesirable deformation and intrusion of the occupant compartment. Frontal force level matching is desirable to ensure that crash energy is appropriately shared between collision partners. Current international consumer and regulation test methods cause frontal crush forces to be mass dependent and require heavier vehicles to be stiffer than lighter vehicles. Earlier studies found this disparity in vehicle force levels caused heavier vehicles to over-crush lighter vehicles and produce undesired occupant compartment deformations. The two compatibility characteristics described above require a *strong and stable occupant compartment* to support energy absorption in frontal structures.

One explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility. An improved and more detailed description of compatibility characteristics is a key point to base any research project that addresses compatibility. For example, structural interaction can likely be divided into different sub areas dealing with geometric placements of structures or the way structures are internally distributing loads in the car. Until a terminology is commonly agreed on, there will be difficulty to design and evaluate a test approach with a general description like structural interaction.

The FIMCAR project worked with two main research activities. One was to develop an evaluation strategy for selecting some combination of suitable test configurations and the second was the technical development activities of specific test candidates. The first activity required terminology, priorities and selection criteria. The second involved crash testing, computer simulation and data processing to develop test procedures as well as assessment criteria and performance limits.

The FIMCAR project was designed to investigate the possibility of combining different configurations to assess compatibility. These tests are the Full Width Rigid Barrier (FWRB), Full Width Deformable Barrier (FWDB), Offset Deformable Barrier (ODB), Progressive Deformable Barrier (PDB) and a Mobile Deformable Barrier (MDB). To achieve this objective the following sub-objectives needed to be addressed:

- to analyse the accident situation of recent cars in order to check whether or not the frontal impact issues reported in previous projects are still relevant in ECE R94 compliant cars
- to identify critical injury mechanisms in frontal impacts
- to define frontal impact issues that should be addressed by the FIMCAR assessment approach
- to develop a rating approach for the individual assessment procedures and the proposed assessment approach
- to further develop off-set, full-width and MDB procedures including their crashworthiness metrics
- to assess different measures to achieve increased compatibility including numerical simulation and vehicle-to-vehicle and vehicle-to-barrier testing
- to develop assessment approaches for vehicle-to-vehicle (M1 vehicle with a total permissible mass less than 3.5 t) frontal compatibility – off-set, full overlap and MDB tests, taking into account overall safety in accident environment
- to propose an assessment approach for vehicle-to-vehicle compatibility aiming at regulation process
- to develop generic and parametric fleet models suitable for the assessment of compatibility (e.g. by improvements of existing generic car models developed within the APROSYS project)
- to analyse the future benefit of using Virtual Testing for the assessment of frontal impact performance
- to harmonise guidelines and regulations within Europe as well as globally with the USA, Japan and other countries
- to conduct a benefit analysis for compatible cars promoted by new compatibility test methods environment
- to develop a methodology for predicting future fleet characteristics

2 MAIN RESULTS

2.1 Accident Analysis

The specific objectives of the accident analysis work were:

- Determine if previously identified compatibility issues are still relevant in current vehicle fleet
    - Structural interaction
    - Frontal force matching
    - Compartment strength in particular for light cars
- Determine nature of injuries and injury mechanisms
    - Body regions injured
    - Injury mechanism
        - Contact with intrusion
        - Contact
        - Deceleration / restraint induced

The main data sources for this accident analysis study were the CCIS and Stats 19 databases from Great Britain and the GIDAS database from Germany. The different sampling and reporting schemes for the detailed databases (CCIS & GIDAS) sometimes do not allow for direct comparisons of the results. However the databases are complementary – CCIS captures more severe collisions highlighting structure and injury issues while GIDAS provides detailed data for a broader range of crash severities. The following results represent the critical points for further development of test procedures in FIMCAR

<u>Compatibility issues</u>

- Poor structural interaction has been observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.
    - In CCIS, structural interaction problems were identified in 40% of fatal and 36% of MAIS 2+ injured cases. However, it is only in cases where there was intrusion present (25% of fatal and 12% of MAIS 2+ cases) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. This is because in cases with intrusion improved structural interaction will increase the energy absorption capability of the car's front-end and thus reduce the intrusion. This, in turn, will help decrease the casualty's injuries caused by contact with intrusion. In cases without intrusion improved structural interaction will change the shape of the compartment deceleration pulse which may or may not help decrease the casualty's injuries depending on the response of the restraint system.

  It should be noted that in 23% of the CCIS fatal cases the accident severity was so high that it was not possible to determine whether or not a compatibility issue had occurred.
- Frontal force and/or compartment strength mismatch issues between cars in the current fleet appear[1] to be less of an issue than poor structural interaction.

[1] Note: structural interaction problems could be masking frontal force mismatch problems

  - In CCIS, for all accidents, force and/or compartment strength mismatch problems were identified for 8% of fatal and 2% MAIS 2+ survived occupants. However, it should be noted that force and/or compartment strength mismatch problems can only be objectively identified for accidents in which there is compartment intrusion into the vehicle.
  - In CCIS, for car-to-car impacts force and/or compartment strength mismatch problems identified for 9% of fatal and 3% MAIS 2+ survived occupants
- Compartment strength of vehicles is still an issue in the current vehicle fleet.
  - Occupants with injuries caused by contact with intrusion CCIS 25%, GIDAS 12% of MAIS 2+ injured occupants
  - When an occupant sustains an injury caused by 'contact with intrusion' in the majority of cases it is the most severe injury, often a leg or thorax injury but sometimes a head or arm injury.
- In a matched pair analysis of car-to-car impacts a relationship was found between mass ratio[2] and driver injury severity, namely the higher the mass ratio the higher the driver injury severity. However, no such relationship was found between mass ratio and intrusion. The implications of this are that intrusion (and hence compartment strength) is not the major contributory factor to more severe injuries in the lighter car in a car-to-car impact. However, it should be noted that the data sample used for this analysis was relatively small and hence confidence in this result is limited. In addition the result may have been confounded by the age of the vehicle (newer vehicles generally have better compartment integrity) and the age of the occupant.
- Compartment strength is a particular problem in collisions with HGVs and objects, with these collisions having a high proportion of fatal and MAIS 2+ injuries
  - In CCIS, 31% of car-HGV cases resulted in intrusion in the car, compared to 25% for car-to-car cases
  - In GIDAS, 20% of car-HGV cases had MAIS 2+ injury severity for the car occupant, compared with 7% for car-to-car cases

<u>Injury patterns</u>

- AIS 2+ injuries to the thorax are the most prevalent. AIS 2+ injuries are also frequently sustained by the head, legs and arms.
  - Over 80% of fatally injured occupants and 35% of MAIS 2+ survived occupants sustained AIS 2+ thorax injuries in CCIS
- AIS 2+ injuries related to the restraint system (i.e. those caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injury by contact with other car interior structures) are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not.
  - Over 40% MAIS 2+ occupants sustained AIS 2+ injury attributed to restraint loading in both CCIS and GIDAS datasets.
- Analysis of injury mechanisms in CCIS found that 45% of MAIS 2+ injured occupants had an AIS 2+ injury related to the 'restraint system', 40% had an AIS 2+ injury caused by 'contact with no intrusion' and 25% had an AIS 2+ injury caused by 'contact with

[2] mass ratio above 1 means that the partner vehicle is heavier

intrusion' In the majority of cases these injuries were the most serious injuries that the occupant had.
  - When the most severe injury was related to the 'restraint system' the injury was mainly to the thorax (62%) with some to the arms (21%) (clavicle fractures).
  - When the most severe injury was related to the 'contact no intrusion' the injury was mainly to the legs (42%) with some to the arms (30%) (clavicle fractures) and thorax (12%).
  - When the most severe injury was related to the 'contact with intrusion' the injury was mainly to the legs (46%) and thorax (30%).
- For accidents for which there is intrusion, for MAIS 2+ injured occupants AIS 2+ injuries to the legs are the most prevalent
  - Where intrusion was present about 70% MAIS 2+ occupants sustained AIS 2+ leg injuries in CCIS
  - Note: about 40% sustained AIS 2+ thorax injuries
- AIS 2+ injuries resulting from contact with the intrusion occur in a large proportion of cases where compartment intrusion is present
  - 65% of MAIS 2+ occupants in cars with intrusion sustained AIS 2+ injury attributed to contact with intrusion (CCIS)
- High proportion of fatal and MAIS 2+ injuries in cases with high overlap (>75%)
  - In GIDAS, 41% of MAIS 2+ survived were in high overlap cases
  - In CCIS, 40% of MAIS 2+ survived and 31% of fatal occupants were in crashes with high overlap
- GIDAS analysis showed that the proportion of MAIS 2+ injuries due to acceleration loading (i.e. injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures) increased for higher overlap cases, whilst proportion of MAIS 2+ injuries due to contact with intrusion increased for lower overlap cases
  - In GIDAS 25% of MAIS 2+ survived were in low overlap cases indicating possible issues with low overlap and/or narrow object impacts. However, much lower percentages were seen in car-to-car impacts and CCIS data.
- Greater proportion of fatal and MAIS 2+ injuries for elderly occupants compared with other age groups
  - In CCIS dataset, occupants over 60 years old represent 18% of injured occupants, however account for 52% of fatalities and 25% of MAIS 2+ survived occupants
- In GIDAS, serious injuries (AIS 2+) due to acceleration loading (restraints) could be identified to occur more often for women than men and are linked with slightly higher proportions for front passengers than drivers.

2.2 Test Selection Approach

One explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility. An improved and more detailed description of compatibility characteristics is a key point to base any research project that addresses compatibility. For example, structural interaction can likely be divided into different sub areas dealing with geometrical placements of structures or the way structures are internally distributing loads in the car. Until a terminology is commonly agreed on, there will be difficulty to design and evaluate a test approach with a general description like structural interaction.

From a review of previous research and additional accident analysis, FIMCAR members have established and defined a list of issues that describe the challenges in vehicle crashworthiness. The consortium agreed that:

- Compatibility consists of self and partner protection.
- Improved compatibility will decrease the injury risks for occupants in single and multiple vehicle accidents.
- Compatible vehicles will deform in a stable manner allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved.

It is important to separate the physical test process from the assessment of the test results for a test configuration. The assessment of compatibility comes when a combination of test configurations and assessment procedures are used to evaluate vehicle performance. The following definitions were developed within FIMCAR to address technical test developments:

- The *test procedure* specifies the test protocol which includes the barrier face, test speed, overlap etc. That means that the test procedure is also a description of how the test is executed.
- The *assessment procedure* includes the test procedure and the definition of the compatibility metrics. The signal processing requirements and performance criteria are identified.
- The *assessment approach* is then the final combination of the assessment procedures that should evaluate the total safety performance of a vehicle for partner and self protection issues.

In order to address compatibility, a detailed list of compatibility characteristics were identified and prioritised by the consortium.

A frontal impact and compatibility description and prioritisation approach was started early in the FIMCAR project. The issues were divided into 4 main groups: Structural Interaction, Compartment Strength, Frontend Force / Deformation, Deceleration Pulse and Restraint System Assessment. These groupings were further broken down into sub groups to focus the test candidate development. The items listed in Figure 2.1 could be identified in previous research activities. Some of the subtopics could be identified as self protection or partner protection issues and the main idea was to provide a comprehensive description of all frontal impact issues. In brief:

- <u>Structural Interaction</u> describes how the structures of a vehicle deform at the local level when interacting with a collision partner. To achieve good structural interaction there must be some type of *structural alignment* which requires that there are corresponding structures in each collision partner that are geometrically and structurally capable of interacting with the opponents main crash structures. It is preferable that this alignment occurs as early as possible in the crash to maximise the energy absorption and ride down characteristics for the occupant. As it is not possible to achieve good structural alignment for all possible collision types and collision partners, it is desirable to have good *horizontal and vertical load spreading* so that a robust and stable deformation of all structures can be facilitated.

- Compartment Strength is important to ensure the passenger compartment is free of intrusions and that the frontal energy absorbing structures have a stable reaction base. All vehicles must exhibit good compartment *integrity in single vehicle collisions* such as crashes into objects and HGV. Smaller vehicles have extra risks when colliding with heavier vehicles and one can identify the need for some vehicles to have higher requirements for compartment *integrity for self protection in vehicle-to-vehicle collisions.*
- Front End Force/Deformation Characteristics have two complementary functions depending on the vehicle mass. There is a clear relationship between vehicle deformation forces and vehicle size and there is an interest to control the *deformation forces in frontal structures* when different vehicles collide. Although difficult to guarantee, it is important to not create situations where one vehicle is too stiff and over-crushes a partner vehicle and exploits the energy absorption of the partner vehicle before its own energy absorption processes begins. Similarly it is not desirable to create a vehicle that does not deform in, for example, a single vehicle impact. Insufficient *energy absorption management* will produce vehicles that do not suitably protect an occupant. One can view deformation forces in frontal structures as a means to ensure partner protection and energy absorption management as a self protection issue.
- Deceleration Pulse and Restraint System issues are important parts of a vehicle safety assessment. It is desirable to evaluate the *sensing system for deployable systems* to different crash pulses and deformation patterns to avoid single point optimisation of safety performance. There should also be sufficient *capacity of restraint system* so that an occupant is protected for a high severity impact that could be foreseen. An additional point that is interesting to investigate (but may be difficult to implement as a regulation) is the *evaluation of occupant safety in a partner vehicle.*

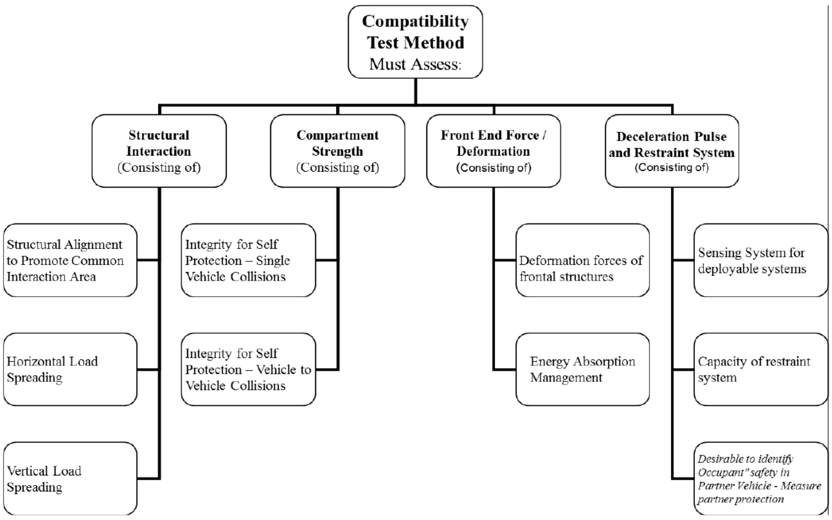


Figure 2.1: Compatibility characteristics.

The main sources for establishing the priorities and selection criteria were the FIMCAR accident analysis analysing frontal impact accidents of UN-ECE Regulation 94 compliant cars

(FIMCAR Deliverable D1.1 [Thompson 2013]) and the experts present in the FIMCAR meetings.

The high proportion of MAIS 2+ injuries in accidents with large overlap reinforced the need for a test condition that requires a vehicle safety system (comprising the frontal structural and occupant restraint system) is able to withstand a high deceleration, large overlap condition that is not addressed by the current UN-ECE Regulation 94 requirements. Based on the information in Figure 2.1 and FIMCAR Deliverable D1.1 [Thompson 2013], an updated list of critical compatibility requirements could be developed. In addition, the top level issues described in Figure 2.1 could be reviewed and prioritised in the format shown in Table 1.

Table 1: Main compatibility topics and associated priorities.

	Assessment requirements							
	Structural Interaction		Front End Force / Deformation (Consisting of)		Compartment integrity		Restraint system	
	Alignment	Load Spreading (Load paths / connections)	Deformation forces of frontal structures	Energy Absorption Management	Sufficient for single vehicle accident	Enhanced for light vehicles in vehicle to vehicle accident	(Assess over range of pulses)	Test Restraint Capacity
Priorities For FIMCAR	1	1	2	1	1	2	1	1

Priority 1 items are those that the consortium identified as important for FIMCAR to resolve within the project while Priority 2 items were important but deemed not critical to resolve during the project duration. The most interesting points to note were that the *Deformation forces of frontal structures* and *enhanced compartment strength for light vehicles in vehicle-vehicle issues* were not a high priority for FIMCAR. This is due to the result from the FIMCAR Deliverable D1.1 [Thompson 2013] where smaller cars were not found to have a higher risk of intrusion than heavier vehicles. Although this was a conclusion in earlier studies [Faerber 2007], evolution of vehicle safety is resulting in stronger vehicle compartments. As lighter vehicles were not found to have a higher risk of compartment intrusions, even for heavier crash partners, frontal force differences between vehicles were not as critical as perceived earlier. This is a conclusion from a limited dataset and it should be noted that there is still a higher injury risk for small vehicle occupants in car-to-car crashes. Further work is needed to make definitive conclusions but the injury risk for small vehicles seems to now be more related to the higher delta-v a small car experiences rather than its structural capacity.

Table 2: Evaluation criteria and associated priorities.

Priority 1

1 A common interaction zone defined as 406-508 mm (based on US Part 581 zone)
2 Initial Loading of barrier is evaluated above and below 457 mm
3 Vertical Load spreading evaluated in Part 581 zone
4 Vertical Load spreading evaluated between 180 and 406 mm
6 Horizontal load spreading between longitudinal members
8 Current compartment strength requirements maintained
9 Appropriate severity levels for occupant protection
11 Field Relevant pulses in the tests
14 Monitor crash pulses from all test configurations
15 Acceptable Repeatability/Reproducibility performance
16 Appropriate pass/fail thresholds
17 No step effects in metrics
18a) Good cars as rated good
18b) Poor cars as rated poor
19 Detection of vehicle architecture

Priority 2

5 Vertical load spreading above 508 mm
7 Horizontal load spreading beyond longitudinal members
10 Address mass dependent injury risk
12 Two different pulses for restraint system triggering
13 Two different pulses for restraint system capacity

Project discussions of the accident analysis and compatibility requirements and priorities led to a ranking of priority 1 and priority 2 issues that were evaluated in the project, presented in Table 1.

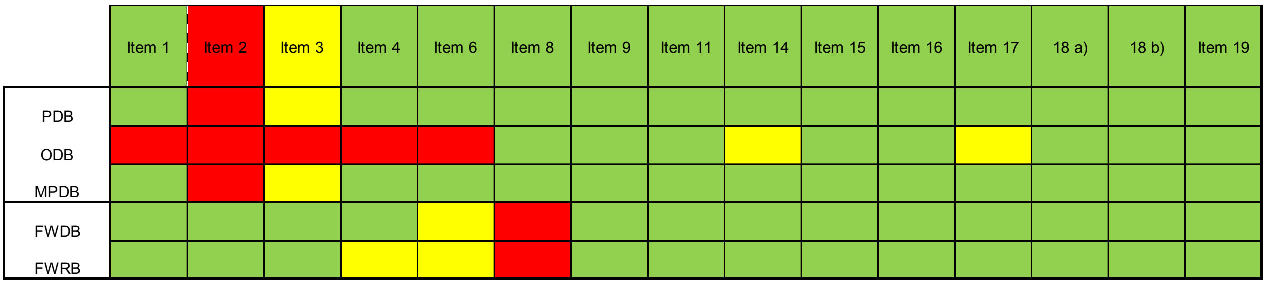


Figure 2.2: Potential of test procedures.

The issues in Table 2 became the basis for evaluating the different full-width and offset test procedures and to see which combination of test and assessment procedures can provide a complete assessment approach for frontal impact and compatibility. The different load cases created in the full-width and offset test configurations facilitates the evaluation of different compatibility characteristics. The potential for each test method is illustrated in Figure 2.2. The benefits and limitations of the different test procedures are apparent and, more importantly, the inability of a single test procedure to fulfil all 15 priority 1 requirements. The main weakness of the offset tests is the ability to assess structural alignment in the beginning of a crash (Item 2) while the full width tests do not suitably assess compartment strength (Item 8).

2.3 Car-to-Car Test Results

The assessment of compatibility in frontal impacts has to address the importance of different vehicle structures. A critical component in the assessment is to identify, quantitatively, what constitutes good performing structures. In particular, the concepts of structural alignment and structural interaction needed to be investigated. Structural alignment is incorporated in candidate compatibility assessments to achieve geometric alignment of identifiable crashworthiness structures. Structural interaction is also a global assessment of how structures interact with a collision partner. The performance of lower vehicle structures in a crash has been identified as important as they may not be evaluated in a structural alignment assessment, but can contribute to structural interaction and thereby improve collision outcome. There has been, however, no clear definition of the characteristics for lower load paths that improve vehicle safety and how these structures manifest themselves in proposed test procedures.

FIMCAR has developed a vehicle crash test program that investigates the performance of vehicle structures using three different test series. The first test series used Super-mini vehicles with different front end architectures. These tests with and without, geometric alignment allowed the effectiveness of a lower load path to be compared to a case without a lower load path. A second set of tests investigated the importance of lower load paths for SUV type vehicles where the main front structures may not align with the main structures in a collision partner, but a lower load path may offset the consequences of this initial misalignment. A final test series investigated how the lower load paths in higher SUV type vehicles influence safety in side impact conditions and thus identify potential side effects of a new assessment procedure.

Results of the test program show that the presence of a lower load path contributes to a more robust performance of the vehicle. The rearward offset of a lower load path could be reviewed and used to quantify when a lower structure design can contribute to structural interaction in both frontal and side impact configurations.

2.4 Simulation Models

In order to reduce testing efforts numerical simulation is a reliable tool for the assessment and optimisation of car design. However, compatibility is an issue exceeding the borders of the vehicle fleet of one manufacturer. Due to confidentiality of the FE models and different software codes at different OEMs it is impossible to crash car models of different manufacturers with each other. To overcome these important limitations, two different approaches for common target vehicles within the FIMCAR project were developed. The Generic Car Models (GCM) are detailed numerical models which represent average cars within different vehicle categories (super-mini, small family car, executive car). Although they are models of cars which will never actually be built, i.e. virtual prototypes, they are of a comparable standard to the models that OEMs build of their cars. The Parametric Car Models (PCM) are also representing average cars of each category but are modelled in a simplified and parametric way. This latter approach allows reduced computational efforts and fast modification of the models.

The GCM models were developed from the three models originally generated by CRF within the past EC project APROSYS, in which the concept of a generic car model was adopted for the first time. These models were successfully used in the research conducted by several partners of that Consortium. For FIMCAR use, these original models were modified and improved with special focus on the front structure design. The overall number of vehicle models was increased with the addition of model variants. For super-mini and small family categories, two models were generated in each class in order to describe the two main architectural/structural car variants that can usually be found on the road, i.e. with and without a third load path in the frontal frame (structural elements below the main rails). The availability of both structural solutions in the GCMs is important for the study of compatibility issues.

Five different models were generated within FIMCAR (2 super-minis, 2 small family cars and one executive). Three different FE codes (LS Dyna, PAM-Crash and RADIOSS) were used to address the software codes used by the consortium. The models can be used to evaluate the behaviour of the crash structure (e.g., crash pulse, deformation characteristics and intrusions). However, no restraint systems are included in the models thus no assessment of dummy readings is possible. For the assessment of the occupant loading conditions the evaluation of the crash pulse and compartment intrusions is necessary.

The model development work consisted mainly of an engineering activity operated on the vehicle models in order to obtain realistic crash behaviour in frontal crashes (full width and offset rigid barriers). Once this realistic behaviour had been obtained from the models in one code environment (LS-Dyna), then the models were translated in the other environments (Radioss and Pam-Crash). The correlation of results between code versions were verified and improved to the levels judged appropriate for the studies to be conducted within the project.

GCMs behave in a realistic manner; this realistic behaviour is the target that guided all their development work and that represents their validation. As the full width rigid barrier test is one of the two crash configurations used for the development of GCMs, comparison with publicly available US NCAP crash test data was used. Figure 2.3 shows the front design of the GCMs.

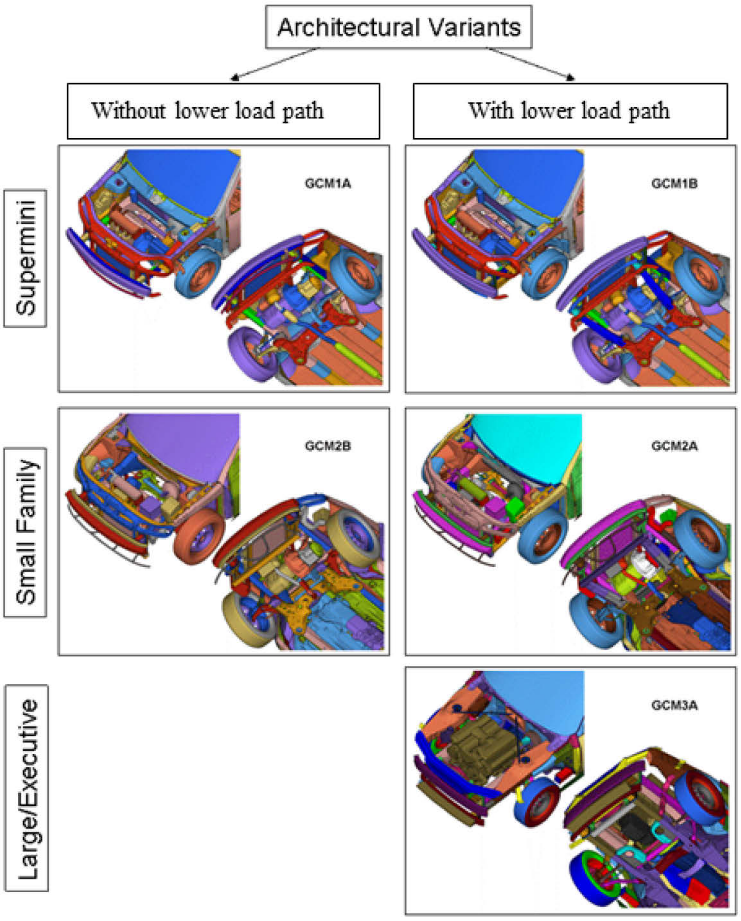


Figure 2.3: Architectural variants of GCMs.

All together three different PCMs were generated (super-mini, large family car and executive) in three different FE codes (LS Dyna, PAM-Crash and RADIOSS). The models can be used to evaluate the behaviour of the crash structure (e.g., crash pulse, deformation characteristics and intrusions). However, no restraint systems are included in the models thus no assessment of dummy readings is possible. For the assessment of the occupant loading conditions the evaluation of the crash pulse is necessary.

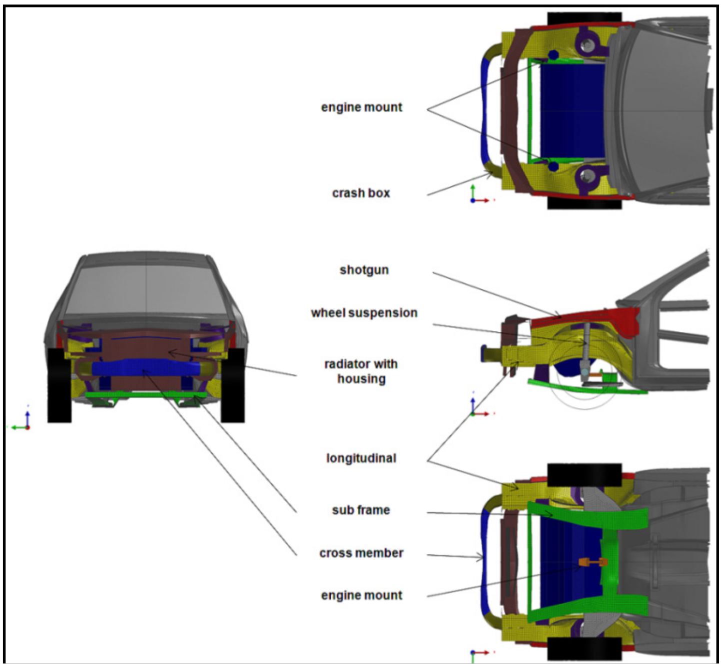


Figure 2.4: Front end structures of the PCMs.

The models were validated using US NCAP crash test data. In addition external dimensions, masses etc. from different cars of the three classes were collected and averaged. Figure 2.4 shows the front design of the PCMs.

2.5 Analysis and Development of Off-set Assessment Procedure

The main candidates for the off-set assessment procedure were the ODB test procedure as currently used for UNECE Regulation 94 and the PDB test procedure as proposed by France for future UNECE regulation.

The current off-set test approaches, most common in vehicle testing, are used in the European frontal directive (96/79/EC) and in consumer tests like Euro NCAP. These consist of an impact into a honeycomb barrier (EEVC barrier) with a 40% overlap. There are no current activities investigating the use of this test configuration for measuring structural interaction, but frontal force levels have been measured using a load cell wall mounted behind the deformable element and was investigated previously [Edwards 2007]. Another off-set test procedure – the Progressive Deformable Barrier (PDB) – has been investigated for structural interaction and frontal force level assessment. This 50% off-set test condition measures the deformation of the honeycomb barrier after the test. The PDB honeycomb is stiffer than the EEVC barrier and becomes progressively stiffer with increased deformation. The barrier deformation is used to analyse the structural interaction and force levels of the tested vehicle.

The main objectives of the off-set test procedure are to address structural alignment, load spreading issues, compartment integrity and the restraint system issues (different test pulses).

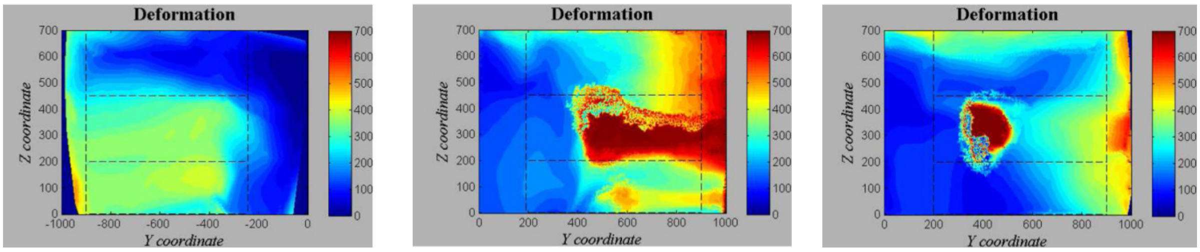
Initial discussions in the FIMCAR project suggested that the existing ODB in UNECE Regulation 94 was not capable of evaluating the compatibility (partner protection) of a vehicle. The PDB became the preferred offset test procedure for further development as it was anticipated that a metric for assessing the load spreading capabilities of a vehicle could be developed during the project. There have also been significant discussions on the ability of the PDB to provide a sufficiently severe test condition for all vehicle masses.

The PDB test is a 50% overlap off-set test which uses deformation measurements from a progressive deformable barrier to assess car's compatibility in terms of partner and self protection. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The 50% overlap and the barrier characteristics allow the PDB to identity the main structures involved in the frontal crash. Geometrical data from previous European research projects (VC-Compat) [Edwards 2007] and IMPROVER [van der Zweep 2006] shown that the main structures of the vehicles will interact with the PDB.

The barrier stiffness of the PDB increases with depth and has upper and lower load levels to represent an actual car structure. The progressive stiffness of the barrier has been designed so that the Equivalent Energy Speed (EES) for the vehicle should be independent of the vehicle's mass. The use of a PDB barrier should thus harmonise the test severity amongst vehicles of different masses by encouraging lighter vehicles to be stronger without increasing the force levels of large vehicles.

The key data used in a PDB test is the post-crash deformations of the barrier. A 3-D image of the barrier is recorded in the computer and the depth and distribution of the deformations are used to assess the vehicle's compatibility characteristics. Although the subjective analysis of the deformed PDB barrier face suggests a good possibility to judge the load spreading capabilities of the tested car (see Figure 2.5) it turned out that it is difficult to mathematically describe a metrics that objectively rates the car.



homogeneous load distribution | strong cross beam but too short and poor homogeneity below cross beam | insufficient cross beam

Figure 2.5: Subjective assessment of PDB barrier deformations.

At the time of the evaluation of the different test candidates, there were clear issues with the metrics being developed for the PDB and, at the time of evaluation, no robust metrics were available for the group. The test criteria proposed for assessing load spreading were based on complicated mathematical concepts and involved quantifying iso-curves for barrier deformations. There were discontinuities when the iso-curves crossed the assessment boundaries and this introduced step effects that were not consistent when applied to different vehicles. An additional issue regarding the test severity for heavier vehicles arose for the PDB and, at the time of evaluation, the comparison of test severity for identical vehicles for PDB and ODB tests could not be presented.

It needs to be noted that at the end of the FIMCAR project a draft (M)PDB metric was presented that analyses the lateral deformation gradients (slopes) of the barrier deformation.

2.6 Analysis and Development of Full-width Assessment Procedure

The main aim of the full-width test procedure is to control a vehicle's structural alignment and to provide a severe deceleration pulse for the assessment of the restraint system.

Two types of full width test were investigated the Full Width Rigid Barrier (FWRB) test and the Full Width Deformable Barrier (FWDB) test. For both tests, the use of Load Cell Wall (LCW) data to control the structural interaction characteristics of a vehicle by controlling the measured force distribution was investigated.

The FWRB test is conducted in many countries (USA, Canada, Japan, etc.) for both regulation and consumer testing programs. Test speeds range from 50 to 56 km/h.

The FWDB test has a 300 mm deformable element. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure. Although essentially the same test configuration as the FWRB, the additional honeycomb is included to attenuate the initial contact with the barrier and introduce more shear forces within the vehicle structure. Past research shows that the deformable element reduces the influence of small, stiff structures such as protruding bolts, and the drive-train loads on the barrier.

For both the FWRB and FWDB tests metrics to assess a vehicle's ability to apply loads in a common interaction zone were developed. The main aim of these metrics is to enforce vertical structural alignment because this is a first basic step to increase the compatibility of car crash outcomes. After a common interaction zone is defined, issues such as horizontal distribution or frontal force can be addressed.

The concept on which this development is based incorporates aspects of the US voluntary commitment for the improvement of the geometric frontal impact compatibility of Light Trucks and Vans (LTVs) [Barbat 2005]; and the current investigations by Japan [Yonezawa 2009]. The concept was decided following the review of metrics developed previously, e.g. AHOF, homogeneity criterion. The aim of the US voluntary commitment is to ensure that LTVs have structure in alignment with a common interaction zone from 16 to 20 inches (406 – 508 mm), further named as "Part 581 zone") measured vertically from the ground to enable better interaction with cars. Current investigations by Japan are researching the feasibility of metrics which assess the forces measured in rows 3 and 4 of the load cell wall.

The full width rigid and full width deformable barrier both provide a hard pulse for the occupant and use similar test instrumentation. The main difference is the time window available for assessing vehicle structures. A rigid barrier may only allow a short assessment duration before the engine contacts the load cell wall and begins to mask the structural forces with high contact loads. The deformable barrier face attenuates the engine contact and allows for a longer evaluation period before the engine contact.

The influence of the barrier face on the measurement capabilities of the load cell wall was important in the decision to choose a FWRB or a FWDB. The FWRB is able to directly measure the structural loads from the vehicle as there is no honeycomb filtering the forces.

However the FWRB could not assess loads in Rows 1&2 that come after the analysis window for structural alignment, sometimes as short as 6 ms. There have been suggestions to modify the FWRB with an override barrier (ORB) when assessing higher vehicle structures such as SUVs [Patel 2009], but FIMCAR data suggests that it may be possible to assess the SEAS that are beneficial for car-to-car collisions by the FWDB while the ORB as present seems not to be able to distinguish sufficiently between beneficial and poor SEAS.

It is expected that the FWDB test results are more representative of real world accident performance w.r.t. to restraint system triggering and stability of energy absorbing structures. Figure 2.6 shows the deformation pattern of the same car in different test configurations. There are similarities in the deformations in the car-to-car and FWDB test where the crash box is not used due bending of the main structures. The deformation pattern of the FWRB test, however, is evenly distributed vertically and laterally and the energy absorption structures like the crash box are well exploited. This shows that cars with good deformation behaviour in FWRB test do not necessarily deform in a stable manner in car-to-car impacts. It is thus difficult to predict car-to-car crash performance from FWRB test results.

FWDB test | FWRB test | car-to-car test

Figure 2.6: Comparison of front structure deformation pattern in different frontal impact tests.

The technical advantage for assessing structural alignment and for testing the cars in a more representative way was for the FWDB while the FWRB offers easier global harmonisation and potentially less test variability due to a deformable face, see Table 3.

Table 3: Advantages of different full-width tests.

FWDB	FWRB
• More representative of real world accident especially in initial stage of impact. • More representative for initial deceleration of vehicle and loading of main rails which is important for sensing of crash for restraint system triggering. • Engine dump loading attenuated, making assessment of vehicle structures that are relevant to crash that are loaded later in the impact, i.e. an assessment can be made of the vehicle's main rails as opposed to its crush cans. • Results in more realistic deformation pattern of the front structure following to shear forces which are not applicable in FWRB • Can detect SEAS structures, so no need for supplementary test, e.g. ORB. • Possibly can assess horizontal structures (bumper beams).	• Effectively already de-facto worldwide standard test so hence would be easier to introduce from harmonisation point of view. • LCW measures vehicle forces directly, i.e. not filtered by deformable element. • No problems with stability of deformable face or possibility of load spreading by deformable face. • More test data available for development of metric

2.7 Analysis and Development of Moving Deformable Barrier Assessment Procedure

One of the test modes investigated during the FIMCAR project to improve frontal impact and compatibility is a so-called Moving Deformable Barrier test (MDB test). This is a frontal test with a moving test vehicle and moving trolley equipped with a deformable element. In various initiatives in Europe and the US this type of test is seen as a next step in the future evaluation of vehicle safety with a good possibility for harmonization. Based on the experience of various projects prior to the FIMCAR project, a test protocol has been drafted in the FIMCAR project. Two main parameters: test speed and trolley mass, key factor to define the severity of the MDB test have been defined during the FIMCAR program.

Using the draft protocol a number of MDB tests have been carried out, the main objectives of the test were:

- assessment of feasibility of the test set up and protocol
- definition of the test severity; trolley mas and impact speed
- assessing of repeatability and reproducibility
- development and validation of compatibility metric / horizontal load spreading

The results of 15 MPDB test have been used for the FIMCAR investigations. In general terms, the tests according the draft protocol were feasible in various laboratories using different test trollies. Special attention is needed for the wheel alignment of trolley and test vehicles to avoid incorrect offsets.

For the explored vehicle mass range, kerb weight from 1000 kg to 2200 kg, a fixed trolley mass of 1500 kg and a test speed of 50 km/h (for vehicle and trolley) results in an acceptable test severity. For vehicles outside this range, for example light electrical vehicles and heavy SUV's, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out to date. These series of tests both showed good results, giving an indication for good R&R; however more tests are needed to make this statement statistically relevant.

Various investigations have been made for compatibility metrics to assess the load spreading of the tested vehicles. It was not possible to define metrics based on load cell wall recordings or trolley accelerations. The metric for horizontal load spreading based on the deformation of the PDB barrier, as defined for the stationary offset test of FIMCAR, is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of the overall vehicle width and a vertical area between 305 and 555 mm (row 3 and row 4 of the Full width load cell) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicles with an even (homogeneous) deformation pattern or a barrier with localised holes.

The FIMCAR project proves that the MPDB test is a good candidate for future frontal compatibility test and assessment activities. More tests and studies are needed to define the test severity for light and heavy vehicles and to confirm the R&R results.

International discussions are needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in the shorter term, as it has advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

2.8 Definition of FIMCAR Frontal Impact Assessment Approach

The list of criteria and their prioritization provided a basis for an objective comparison of the test procedures. The technical development of each test and assessment procedure was documented and its capability to assess each of the requirements was reported. The methods for assessing each requirement varied and were essentially confirmation (yes/no), engineering documentation (data presentation) or assessment with reference vehicles with known properties. The latter case was critical as no single vehicle could be identified as fulfilling all compatibility requirements, but vehicles could be identified that fulfilled one or more compatibility requirements. Lists of physical or numerical vehicle models were developed to document performance in terms of bumper cross beam stiffness, presence of lower load paths, and global performance. Experience in the VC-Compat project suggested that vehicles exhibit a combination of different compatibility characteristics, but specific issues could be isolated in car-to-car tests.

Data from each of the test development work packages in FIMCAR were summarised in a table format based on the items but only the Priority 1 issues were addressed in the evaluation. As expected, there was no single test method that could satisfy all the issues and a combination of test procedures was necessary. As a result, the selection of an assessment approach could be separated into two independent evaluations – one for the full width and one for the offset test configurations.

A key point to note in the following presentation of results is that the initial prioritisation activities and evaluation activities occurred in the first 2 years of the project, before the full assessment metrics for any test procedure were finalised. The goal was to focus the final validation and documentation activities on the most viable test and assessment procedures.

After the initial evaluation of the test procedures, the consortium selected the full width deformable barrier test as the most promising candidate. There were different metrics available that had exhibited promising results. The outstanding issues that needed to be resolved were the selection and validation of the final assessment metric, criteria for occupant injury, and the test speed. Once this was established, integration with the offset test was required.

After selection of the Full Width Deformable Barrier in the FIMCAR assessment approach, further work was needed to finalise the structural alignment metric, confirm a test speed, report the repeatability and reproducibility results and identify the occupant injury criteria. Due to the fact that none of the final FIMCAR test procedures had a capability to assess horizontal load spreading; some further research of the FWDB test was conducted to develop this capability.

FIMCAR Deliverable D3.2 [Adolph 2013] documents the final verification of the metric for evaluating the structural alignment of vehicles. The main results and recommendations of the FWDB investigations in the later stages were:

- <u>FWDB test speed of 50 km/h</u>. This meets the desired test severity of a 50 km/h delta-v identified from accident analysis and also produces a high crash pulse. The test speed was verified by combining the risk to be involved in an accident within a specific delta-v range and the injury risk for that delta-v. The result indicates that the test delta-v should be between 47 and 57 km/h. Taking into account the rebound velocity and to avoid too aggressive test requirements, the test speed was fixed at 50 km/h.
- <u>Structural Alignment</u>: The metric to assess structural alignment currently proposes that a vehicle must exert minimum loads in Rows 3&4 and can use loads in Row 2 to help meet this requirement under certain conditions. The minimum load requirement promotes structural alignment and the credit of loads from Row 2 encourages vertical load spreading. The metric can be defined as:
  - Up to time of 40 msec:
    - $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
    - $F4 \geq [MIN(100, 0.2F_{T40})$ kN
    - $F3 \geq [MIN((100-LR), (0.2F_{T40}-LR))]$
    - where:
      - F_{T40} = Maximum of total LCW force up to time of 40 msec
      - Limit Reduction (LR) = [F2-70] kN and 0 kN ≤ LR ≤ 50* kN
      - *Note values to be confirmed taking into account the new test velocity
- <u>Horizontal Load Spreading:</u> The FWDB test approach is unable to assess the horizontal load spreading in a repeatable manner because of issues such as bottoming out of the barrier face

The FWDB metric was validated using the geometric data for the main structural members and the load cell wall data. There was a good correlation between the physical structures and the metric, see Figure 2.7. Further validation using car-to-car test results in FIMCAR confirmed the metric suitability. The main car-to-car test approach in FIMCAR was to repeat test configurations to with different structural alignments. Only one vehicle, the Super Mini (SM) 1was tested in corresponding FWDB configurations.

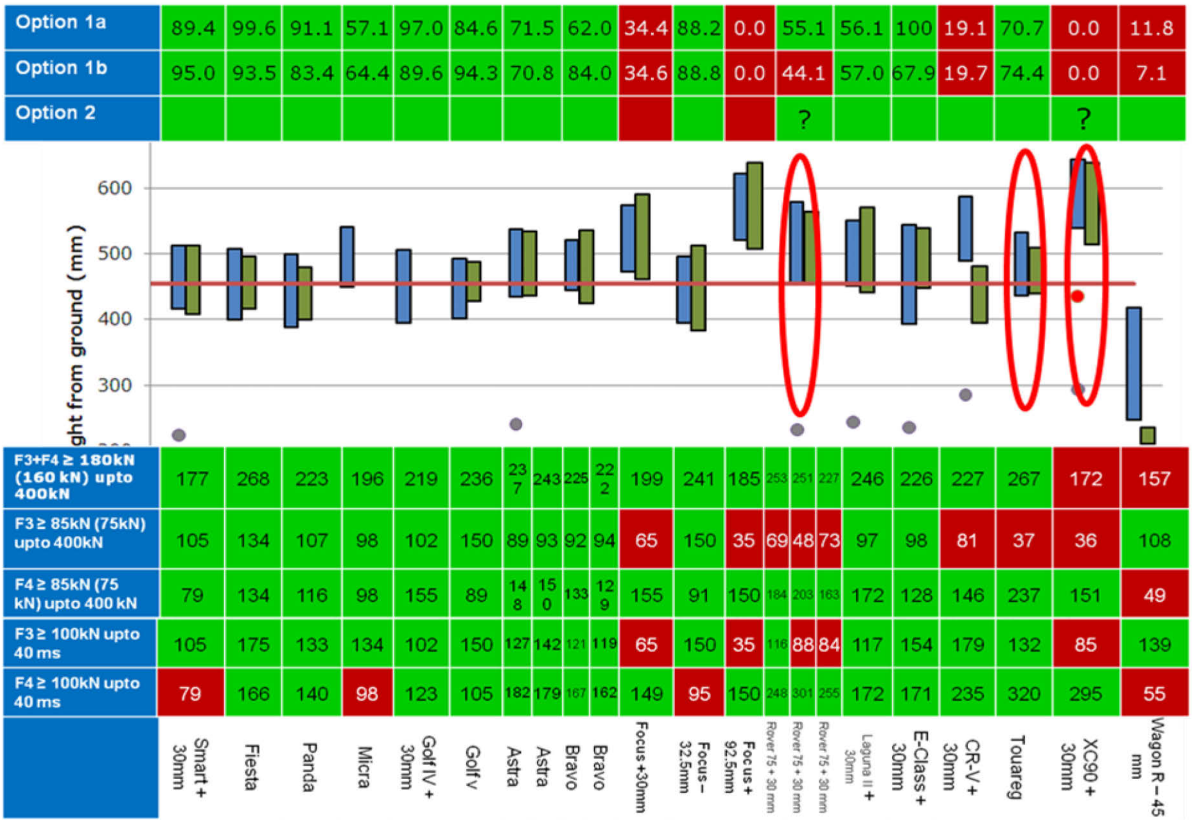


Figure 2.7: Validation of the FWDB metric.

The first result to note is that the vehicles that pass the FWDB metric with both a good distribution between Rows 3 and 4 (fulfilling structural alignment) and also qualifying for a Limit Reduction (LR) had good car-to-car test results regardless of test conditions. SM1 exhibited poor compatibility with a total misalignment of 76 mm while SM2 had good compatibility with a higher (100 mm) misalignment.

The SUV car-to-car tests demonstrated that structural alignment was preferred over the case when PEAS were misaligned but SEAS were still able to provide vertical load spreading. The FWDB were able to detect the vertical load spreading of SUV 2 even with SEAS that were positioned approximately 200 mm behind the bumper cross beam.

The ODB test is proposed as is currently specified in UN-ECE Regulation 94. The current test speed is 56 km/h and no load cell or barrier assessments are proposed. Currently an additional requirement on vehicle intrusions is proposed to ensure all vehicles have a stable occupant compartment. A maximum deformation of 50 mm to the A-pillar is the proposed threshold for this requirement. It is important to note that this requirement will not likely change any of the cars produced for the European market today as Euro NCAP requirements are much more demanding. However, the FIMCAR consortium was reluctant to rely on Euro NCAP assessment for future car safety and proposes the additional requirement to ensure that cars that may not be designed to give good scores in Euro NCAP and may not be tested by Euro NCAP meet a minimum compartment strength requirement. First discussions in international working groups indicated a general acceptance of an additional requirement on the cabin intrusion but the use of A-pillar displacement was considered as being design restrictive by car manufacturers. Therefore a better definition of the requirement seems to be needed.

Two tests for frontal impact requirements are proposed by FIMCAR and each test configuration must be totally fulfilled, independent of the results of the separate tests.

The repeatability and reproducibility of the existing ODB test criteria were not reviewed as they are well known and accepted. The FWDB was investigated through a combination of component and full scale tests. Component tests were conducted at TRL, BASt and UTAC and reported in FIMCAR Deliverable 3.2 [Adolph 2013]. The component tests showed that the variation of load cell readings was consistent between the tests and below 10%. The component tests also showed no crosstalk or load spreading issues that were critical for the metric.

Full scale tests with a FWDB were reviewed from previous projects (VC-COMPAT, APROSYS) and FIMCAR. The earlier projects had limited test data to review - 2 tests with the same vehicle at different test labs. FIMCAR required 3 tests at 2 labs with the same vehicle. The results from the earlier projects showed good repeatability and reproducibility although some were only for two vehicles. The FIMCAR test results did not show good repeatability and reproducibility consistently. The total loads measured in the three tests were within expected test variation, but the 2 tests at the same research institute had slightly different results which resulted in different evaluation outcomes while one of the two tests was sufficiently reproducible to the third test. The chosen test vehicle had demonstrated instability in car-to-car impacts (FIMCAR Deliverable D6.1 [Sandqvist 2013]). The load cell wall at where the tests were repeated did not meet the instrumentation requirements identified by FIMCAR. Because of these issues further validation is required to confirm whether or not the LCW with deformable barrier has good enough repeatability and reproducibility for the regulatory application. However, FIMCAR has concluded that the FWDB repeatability and reproducibility is acceptable, i.e. in line with other crash tests, for cars with a stable front structure in this test mode. For further analysis of R&R the use of a car with a stable front structure and sum forces above 500 kN is recommended. Furthermore the LCW requirements as developed by FIMCAR should be met for the LCWs used.

2.9 Load Cell Wall Certification and Calibration

As load cell wall readings are used for the FWDB metrics it was felt necessary to define a Load Cell Wall (LCW) certification procedure. The procedure consists of the LCW definition and certification requirements in terms of wall flatness. In addition a specification and calibration requirements for the transducers was defined.

Possible approaches for the certification of assembled walls were discussed between partners and Kistler (an LCW manufacturer and external expert). It was decided to only have requirements on wall flatness included in the certification. Other options like full scale trolley tests with well-defined loading surfaces are expensive and include inaccuracies like orthogonallity to the wall. Certification requirements for the wall flatness were based on measurements of three existing walls and an analysis of a trolley test done by BASt.

In addition to the wall certification a load cell specification and calibration section was included in the procedure. It is based on existing procedures for load cells used in crash test dummies. A series of load cells was tested to check and refine requirements set for non-linearity and hysteresis.

Static calibration is currently done for all LCW's in Europe using specifications as set by the LCW manufacturers. However, for usage in test protocols load cell specifications and performance limits are needed. Also a calibration procedure is required that includes information on items like hysteresis and non-linearity. In discussions with partners it was decided to generate a Load Cell Specification and Calibration document based on the following documents:

- SAE J2570: Performance Specifications for Anthropomorphic Test Device Transducers
- ISO 6487: Measurement techniques in impact tests - Instrumentation
- SAE J211: Instrumentation for Impact Test, Rev. 07/2007
- DIN EN ISO 376

Using the references mentioned above specifications and a calibration protocol were defined for the load cells. Parameter values were set based on needs for the FIMCAR metrics and manufacturers specifications of existing walls.

The wall flatness is mainly (or even only) an issue in case a barrier with deformable element is used in front of the LCW. The deformable barrier is backed by a plate of about 2 mm thickness which spreads the loads between neighbouring cells if the load cells are not aligned. Although non-alignment of cell faces can (at least partially) be compensated by adjusting the protective layers it was decided to collect flatness data from a number of existing walls and based on this define requirements for this parameter.

The resulting values for the wall flatness assessment for different load cell walls were used to define a LCW certification procedure (Transducers shall be positioned such that centre point locations and corners of adjacent cells are aligned to have a depth variation of 1 mm or less.). Other requirements like cell size (125x125 mm), ground clearance (80 mm), cell numbering are based on state of the art use procedures of load cell walls.

2.10 Benefit Analysis

Although the number of road accident casualties in Europe is falling the problem still remains substantial. In 2011 there were still over 30,000 road accident fatalities [European Commission 2012]. Approximately half of these were car occupants and about 60 percent of these occurred in frontal impacts. The next stage to improve a car's safety performance in frontal impacts is to improve its compatibility for car-to-car impacts and for collisions against objects and HGVs. Compatibility consists of improving both a car's self and partner protection in a manner such that there is good interaction with the collision partner and the impact energy is absorbed in the car's frontal structures in a controlled way which results in a reduction of injuries. Over the last ten years much research has been performed which has

found that there are four main factors related to a car's compatibility [Edwards 2003; Edwards 2007]. These are structural interaction potential, frontal force matching, compartment strength and the compartment deceleration pulse and related restraint system performance.

The objective of the FIMCAR project was to develop an assessment approach suitable for regulatory application to control a car's frontal impact and compatibility crash performance and perform an associated cost benefit analysis for its implementation.

The cost benefit analysis performed to estimate the effect of the following potential changes to the frontal impact regulation:

- Option 1 – No change and allow current measures to propagate throughout the vehicle fleet.
- Option 2 – Add a full width (FW) test to the current offset Deformable Barrier (ODB) test.
- Option 3 – Add a full width test (FW) and replace the current ODB test with a Progressive Deformable Barrier (PDB) test.

The following conclusions were made:

- For the benefit analysis it was assumed that the introduction of a full-width test with appropriate compatibility and dummy metrics has the potential to address the frontal impact issues under/override related to structural alignment and restraint related acceleration type injuries. Limited potential of the full width test was expected for addressing fork effect issues. It was also assumed that the replacement of the ODB by the PDB/MPDB test procedure with an appropriate homogeneity metric had the potential to address the frontal impact issues under/override related to vertical load spreading, fork effect and low overlap as well as frontal force matching/compartment strength.
- The benefits of three potential changes to the frontal impact regulation were calculated for GB and Germany and scaled to give an indicative estimate for Europe.
    - For Option 1 'No change', a small benefit of about 2.0% or less of all car occupant Killed and Seriously Injured (KSI) casualties was estimated;
    - For Option 2 'Add FW test: Benefit of 5% to 12% of all car occupant KSI casualties was estimated. It was shown that this benefit consisted of:
        - Structural alignment (under/override related to structural alignment): 0.3% - 0.8%. However, it should be noted that the benefit related to structural alignment was likely under-estimated.
        - Restraint system:(restraint related deceleration related injuries): 5% - 11%
    - For Option 3 'Add FW test and replace ODB test with PDB test' 9% - 14% of all car occupant KSI casualties.
    - Note: Benefit percentages for Options 2 and 3 do not include the benefit of Option 1 'No change'.
- Break-even costs for options 2 and 3 were calculated. Comparison of these costs with costs estimated by previous projects indicated that the monetary value of the benefits of implementing Option 2 should be greater than the costs to modify the cars for restraint system changes. However, further work is needed to determine precisely what changes would be needed to deliver the injury reduction assumed for the benefit analysis and precisely what test configuration (in particular dummies) and performance limits would be needed to enforce these changes.

The following points should be noted:

- The benefit was calculated assuming the implementation of complete assessment procedures. However, appropriate dummy assessment values and dummy selection have not been addressed by FIMCAR and appropriate PDB/MPDB metrics are not yet established.
- Possible further potential benefits from the definition of a common interaction zone related to truck underrun protection and roadside guard rails were not considered in the study.

2.11 Influence of FIMCAR Assessment Approach on other Impact Types

The objective of this part was to describe the expected influence of the candidate test procedures developed in FIMCAR for frontal impact on other impact types. The other impact types of primary interest are side impact, collisions with road restraint systems (e.g. guardrails) and heavy goods vehicle impacts. These collision types were chosen as they involve structures that can be adapted to improve safety. Collisions with vulnerable road users (VRU) were not explicitly investigated in FIMCAR. It is expected that the vehicle structures of interest in FIMCAR can be designed into a VRU friendly shell.

Information used for this analysis came from simulations and car-to-car crash tests conducted in FIMCAR or review of previous research. The three test configurations (full width, offset, and moving deformable barriers) were the input to the FIMCAR selection process. There are 3 different types of offset tests and 2 different full width tests. During the project test procedures could be divided into 3 groups that provide different influences or outcomes on vehicle designs:

1. The ODB barrier provides a method to assess part of the vehicles energy absorption capabilities and compartment test in one test
2. The FWRB and FWDB have similar capabilities to control structural alignment, further assess energy absorption capabilities, and promote the improvements in the occupant restraint system for high deceleration impacts.
3. The PDB and MPDB can be used to promote better load spreading in the vehicle structures, in addition to assessing energy absorption and occupant compartment strength in an offset configuration.

The review of how all candidates would affect vehicle performance in other impacts (beside front-to-front vehicle or frontal impacts with fixed obstacles) is reported in this section to support the benefit analysis reported in FIMCAR. The grouping presented above is used to discuss all 5 test candidates using similarities between certain tests and thereby simplify the discussion.

The common theme is the potential to structurally align vehicle components with the opposing structures. In some cases, like truck RUPs (Rear Underrun Protection), requirements of the collision partner are not ideal for passenger vehicle designs. Introduction of performance requirements that harmonise geometric alignment will support future harmonisation of crashworthiness designs, independent of passenger cars. International harmonisation of concepts like the common interaction zone will improve future vehicle and infrastructure safety performance.

Stiffness issues with current vehicle designs are not expected to be affected negatively by the FIMCAR approach. The combination of a FWDB and ODB will create a balanced frontal stiffness that cannot be expected to be softer than vehicle side structures, nor stiffer than HGV frames. Current compartment strength needs to be maintained and the frontal stiffness can be tuned to appropriate levels through the combined full width and offset test requirements.

The current test candidates and final assessment procedure selected by FIMCAR do not have any obvious negative implications for side impacts, HGV impacts, nor impacts with road equipment. The worst case scenario is that the introduction of a FW metric with minimum load requirements in Rows 3&4 can lead to sub-optimization and worsened horizontal load spreading. This risk is small and the selection of a FWDB will likely mitigate this side effect. The deformable barrier dampens the peak loads and introduces a need to have larger contact surfaces to generate sufficient loads in the assessment area.

The current assessment approach in FIMCAR may introduce limited improvements for the investigated collisions, but it is expected that the harmonization of interaction areas of HGV and road side equipment will allow to a convergence to compatible structural designs in the road and traffic network.

2.12 Potential of Simulation Tools Towards the Evaluation of Compatibility

For the assessment of vehicle safety in frontal collisions compatibility (which consist of self and partner protection) between opponents is crucial. The use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

A review of the use of Virtual Testing (VT) in today's European vehicle and product type approval, and the on-going work for future implementation of VT in vehicle type approval and rating is the basis for the estimation of the potential of simulation tools. Combined with the experience from the use of simulation tools in the FIMCAR project, a 4-step roadmap for implementation of VT tools in the compatibility development is proposed.

Step 1

2013 - 2020: further evolution of GCMs concept (Generic Car Models) and consequent availability of first agreed/recognised reference VT model family for regulatory and/or rating application, with associated definition of verification and validation procedures. Convergence towards PGCMs concept (Parametric Generic Car Models) for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models are then capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020 - 2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly i.e. through indicators like OLC (Occupant Load Criterion) or other similar criteria as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted for type approval model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025 - 2030: first full vehicle-crash regulations (type approval and even self-certification) for car-to-car compatibility based on full VT (structural behaviour and dummy biomechanical response based on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030 - 2040: VT maturity reached, with type approval based on full system simulations (structural and biomechanical behaviour included, with human body models (HBM) as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the protocol).

3 POTENTIAL IMPACT

The main objective of the FIMCAR project was to develop a proposal for an assessment approach for future frontal impact regulation for UNECE. During the development the FIMCAR partners discussed the interim findings with external experts, e.g., during two workshops, in meetings of the currently active Informal Group of Frontal Impact of GRSP that has the mandate to propose a new UNECE frontal impact regulation, Euro NCAP amongst others. This communication guided partially the FIMCAR decisions and helped to make external groups aware of the project's activities.

The activities and results in FIMCAR were discussed in both UNECE and Euro NCAP working groups and have resulted in significant discussions external to the project. FIMCAR has been instrumental in raising the discussions on compatibility in external, international working groups and will result in changes in both Euro NCAP and Regulation 94 in the near term (2014-2017)

The GRSP Informal Group on Frontal Impact already considered the FIMCAR results as valuable input for their own decisions, which in the end might be different to the FIMCAR decisions, as the scope to be considered might be different. The latest discussions indicate that a full width test is an accepted requirement for R94 testing. FIMCAR has contributed to the motivation and test speed for a Full Width test. The barrier face and evaluation criteria are still under discussion.

The Euro NCAP technical working group on frontal impact has identified the full width rigid barrier as a new test requirement for the consumer test program. The inclusion of a 5%ile female dummy decision may also be a result of both FIMCAR and parallel project Thorax. It is important to note the Euro NCAP has had different decisions on the barrier face and underlines the need for larger European projects to deliver qualified data for review. The appropriateness of the decisions taken by external parties can later be evaluated with the FIMCAR data.

According to the conducted benefit analysis approx. 5 – 12 % of the European killed or seriously injured people would benefit from the implementation of the FIMCAR results.

3.1 Additional Benefits of the FIMCAR Project

While vehicle safety was the main goal of the project, the results of the project provide important information for future vehicle designs that may have other consequences in terms of environmental impact and new economic benefits. The results of interest are the structural architecture of the vehicles and applications of virtual testing.

Many research projects had proposed that multiple load path vehicles were advantageous for compatibility. FIMCAR was the first to really document the type of structures most beneficial using objective data. The use of lower load paths that are not too far rear of the bumper should lead manufacturers to modify their designs for more robust and efficient forward structures. A direct benefit could be anticipated by the reduction of material needed to design a single load path vehicle in terms of both its longitudinal structure and anchorage in the passenger compartment. Cantilever type structures (i.e., Single load path) tend to be less optimised for mass than a multiple support structure. Moves to this design approach in Europe can lead to both more safety/unit mass as well spur increased European industrial activities in alternative material and production technologies. Informal discussions with industrial partners indicate some activities are already starting in this area.

FIMCAR had considerable model development activities related to GCM and PCM vehicle models. The application of these models was beneficial for the project and highlights how the design process for vehicles requires less time and materials. While physical testing is still needed and encouraged, there are identified applications for simulations in the homologation process that can start reducing the financial burden on industry. A particular problem is the increased level of documentation for safety performance that has historically been based on experimental data. The subsequent integration of virtual testing into the type approval process will provide for better real world safety without exponentially increasing the testing burden on the manufacturer. Virtual testing of worst case vehicle variants in the future is one way to reduce costs for testing while providing guaranteed safety with complementary test and simulation data.

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FIMCAR
II - Accident Analysis

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach has been defined to date. Taking into account the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) and the EC funded FP5 VC-COMPAT project activities, two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in today's research programmes.

The overall objective of the FIMCAR project is to complete the development of the candidate test procedures and propose a set of test procedures suitable for regulatory application to assess and control a vehicle's frontal impact and compatibility crash safety. In addition an associated cost benefit analysis should be performed.

The specific objectives of the work reported in this deliverable were:

- Determine if previously identified compatibility issues are still relevant in current vehicle fleet
    - Structural interaction
    - Frontal force matching
    - Compartment strength in particular for light cars
- Determine nature of injuries and injury mechanisms
    - Body regions injured
    - Injury mechanism
        - Contact with intrusion
        - Contact
        - Deceleration / restraint induced

The main data sources for this report were the CCIS and Stats 19 databases from Great Britain and the GIDAS database from Germany. The different sampling and reporting schemes for the detailed databases (CCIS & GIDAS) sometimes do not allow for direct comparisons of the results. However the databases are complementary – CCIS captures more severe collisions highlighting structure and injury issues while GIDAS provides detailed data for a broader range of crash severities. The following results represent the critical points for further development of test procedures in FIMCAR

<u>Compatibility issues</u>

- Poor structural interaction has been observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.
    - In CCIS, structural interaction problems were identified in 40% of fatal and 36% of MAIS 2+ injured cases. However, it is only in cases where there was intrusion present (25% of fatal and 12% of MAIS 2+ cases) that it can be said definitely that improved structural interaction would have improved the safety

performance of the car. This is because in cases with intrusion improved structural interaction will increase the energy absorption capability of the car's front-end and thus reduce the intrusion. This, in turn, will help decrease the casualty's injuries caused by contact with intrusion. In cases without intrusion improved structural interaction will change the shape of the compartment deceleration pulse which may or may not help decrease the casualty's injuries depending on the response of the restraint system.

It should be noted that in 23% of the CCIS fatal cases the accident severity was so high that it was not possible to determine whether or not a compatibility issue had occurred.

- Frontal force and/or compartment strength mismatch issues between cars in the current fleet appear[1] to be less of an issue than poor structural interaction.
    - In CCIS, for all accidents, force and/or compartment strength mismatch problems were identified for 8% of fatal and 2% MAIS 2+ survived occupants in CCIS. However, it should be noted that force and/or compartment strength mismatch problems can only be objectively identified for accidents in which there is compartment intrusion into the vehicle.
    - In CCIS, for car-to-car impacts force and/or compartment strength mismatch problems identified for 9% of fatal and 3% MAIS 2+ survived occupants
- Compartment strength of vehicles is still an issue in the current vehicle fleet.
    - Occupants with injuries caused by contact with intrusion CCIS 25%, GIDAS 12% of MAIS 2+ injured occupants
    - When an occupant sustains an injury caused by 'contact with intrusion' in the majority of cases it is the most severe injury, often a leg or thorax injury but sometimes a head or arm injury.
- In a matched pair analysis of car-to-car impacts a relationship was found between mass ratio and driver injury severity, namely the higher the mass ratio the higher the driver injury severity (note: mass ratio above 1 means that the partner vehicle is heavier). However, no such relationship was found between mass ratio and intrusion. The implications of this are that intrusion (and hence compartment strength) is not the major contributory factor to more severe injuries in the lighter car in a car-to-car impact. However, it should be noted that the data sample used for this analysis was relatively small and hence confidence in this result is limited. In addition the result may have been confounded by the age of the vehicle (newer vehicles generally have better compartment integrity) and the age of the occupant.
- Compartment strength is a particular problem in collisions with HGVs and objects, with these collisions having a high proportion of fatal and MAIS 2+ injuries
    - In CCIS, 31% of car-HGV cases resulted in intrusion in the car, compared to 25% for car-to-car cases
    - In GIDAS, 20% of car-HGV cases had MAIS 2+ injury severity for the car occupant, compared with 7% for car-to-car cases

[1] Note: structural interaction problems could be masking frontal force mismatch problems

Injury patterns

- AIS 2+ injuries to the thorax are the most prevalent. AIS 2+ injuries are also frequently sustained by the head, legs and arms.
    - Over 80% of fatally injured occupants and 35% of MAIS 2+ survived occupants sustained AIS 2+ thorax injuries in CCIS
- AIS 2+ injuries related to the restraint system (i.e. those caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injury by contact with other car interior structures) are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not.
    - Over 40% MAIS 2+ occupants sustained AIS 2+ injury attributed to restraint loading in both CCIS and GIDAS datasets.
- Analysis of injury mechanisms in CCIS found that 45% of MAIS 2+ injured occupants had an AIS 2+ injury related to the 'restraint system', 40% had an AIS 2+ injury caused by 'contact with no intrusion' and 25% had an AIS 2+ injury caused by 'contact with intrusion' In the majority of cases these injuries were the most serious injuries that the occupant had.
    - When the most severe injury was related to the 'restraint system' the injury was mainly to the thorax (62%) with some to the arms (21%) (clavicle fractures).
    - When the most severe injury was related to the 'contact no intrusion' the injury was mainly to the legs (42%) with some to the arms (30%) (clavicle fractures) and thorax (12%).
    - When the most severe injury was related to the 'contact with intrusion' the injury was mainly to the legs (46%) and thorax (30%).
- For accidents for which there is intrusion, for MAIS 2+ injured occupants AIS 2+ injuries to the legs are the most prevalent
    - Where intrusion was present about 70% MAIS 2+ occupants sustained AIS 2+ leg injuries in CCIS
    - Note: about 40% sustained AIS 2+ thorax injuries
- AIS 2+ injuries resulting from contact with intrusion occur in a large proportion of cases where compartment intrusion is present
    - 65% of MAIS 2+ occupants in cars with intrusion sustained AIS 2+ injury attributed to contact with intrusion (CCIS)
- High proportion of fatal and MAIS 2+ injuries in cases with high overlap (>75%)
    - In GIDAS, 41% of MAIS 2+ survived were in high overlap cases
    - In CCIS, 40% of MAIS 2+ survived and 31% of fatal occupants were in crashes with high overlap
- GIDAS analysis showed that the proportion of MAIS 2+ injuries due to acceleration loading (i.e. injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures) increased for higher overlap cases, whilst proportion of MAIS 2+ injuries due to contact with intrusion increased for lower overlap cases
    - In GIDAS 25% of MAIS 2+ survived were in low overlap cases indicating possible issues with low overlap and/or narrow object impacts. However, much lower percentages were seen in car-to-car impacts and CCIS data.

- Greater proportion of fatal and MAIS 2+ injuries for elderly occupants compared with other age groups
    - In CCIS dataset, occupants over 60 years old represent 18% of injured occupants, however account for 52% of fatalities and 25% of MAIS 2+ survived occupants
- In GIDAS, serious injuries (AIS 2+) due to acceleration loading (restraints) could be identified to occur more often for women than men and are linked with slightly higher proportions for front passengers than drivers.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self and partner-protection level) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 [Faerber 2007] and the FP5 VC-COMPAT [Edwards 2007] project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition, another procedure (tests with a moving deformable barrier) is under discussion in today's research programmes.

Within the FIMCAR project, different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objectives of this work for this deliverable were:

- Determine if previously identified compatibility issues are still relevant in current vehicle fleet
    - Structural interaction
    - Frontal force matching
    - Compartment strength in particular for light cars
- Determine nature of injuries and injury mechanisms
    - Body regions injured
    - Injury mechanism
        - Contact with intrusion
        - Contact
        - Deceleration / restraint induced

1.3 Structure of this Deliverable

This deliverable starts with a 'Background' section in which previous relevant accident analysis work is reviewed. Next the 'Approach' section describes the basis for how the analysis work was performed. This is followed by the 'Description of Accident Databases' section which describes the GB CCIS and German GIDAS accident databases used for the analysis work performed. The results of the GB accident analysis work using the CCIS database and the German accident analysis work using the GIDAS database are described in the 'GB Accident Analysis' and 'German Accident Analysis' sections respectively. This is followed by a discussion section in which the results of the GB and German analyses are compared, which in turn is followed by the 'Summary of Conclusions' section.

2 BACKGROUND

Compatibility research has depended on the use of accident data to identify both the critical issues that safety issues making up compatibility as well as indicating the size of the problem. The FIMCAR project is the continuation of previous research undertaken in Europe but has also made an important step forward – specifically looking at the safety of newer model vehicles.

The earlier work in EEVC WG 15 [Faerber 2007] and VC-Compat [Edwards 2007] was based on accident data collected before 2004-2005. This time period was shortly after UNECE Regulation 94 became mandatory for all newly registered European vehicles (1st Oct 2003). This presents two issues for interpretation of the data. The first is that the accident data set available contained very few vehicles that were built after 2000. New vehicle models are not involved in accidents in significant numbers until a few years have elapsed. The second issue is that the new vehicles introduced between 1998 and 2003 did not necessarily have to meet Regulation 94 (phase in period). Thus the accident data available in previous research contained a range of vehicle designs that did not meet current regulations.

The accident analysis and benefit approach taken in VC-Compat is presented in Figure 2.1. The target population was based on pessimistic or optimistic assumptions of which vehicle occupants would benefit from compatibility improvements. These assumptions were based on accident configuration parameters such as the crash severity, expressed in EES/ETS,[2] the direction of vehicle loading and the degree of overlap. From the GB and German approaches documented in [Edwards 2007] a European estimate of the benefit for compatibility was estimated to be a 4%-8% reduction in fatalities and a 5%-13% reduction in serious injuries for car-to-car crashes.

A strategy for the accident analysis conducted in FIMCAR, developed from the GRSP informal working group on frontal impact, was that accident analysis should be limited to vehicles fulfilling Regulation 94. The main focus of FIMCAR has been to continue using the detailed databases available in the UK and Germany in order to study specific crash mechanisms that influence vehicle safety. The remainder of this section will report the recent research activities relevant to the FIMCAR project.

[2] Equivalent Energy Speed (describing the deformation energy by the velocity which would be necessary to generate the deformation) / Estimated Test Speed (test speed of the vehicle against a rigid fixed barrier that would cause the same deformation)
Note: EES and ETS are very similar measures

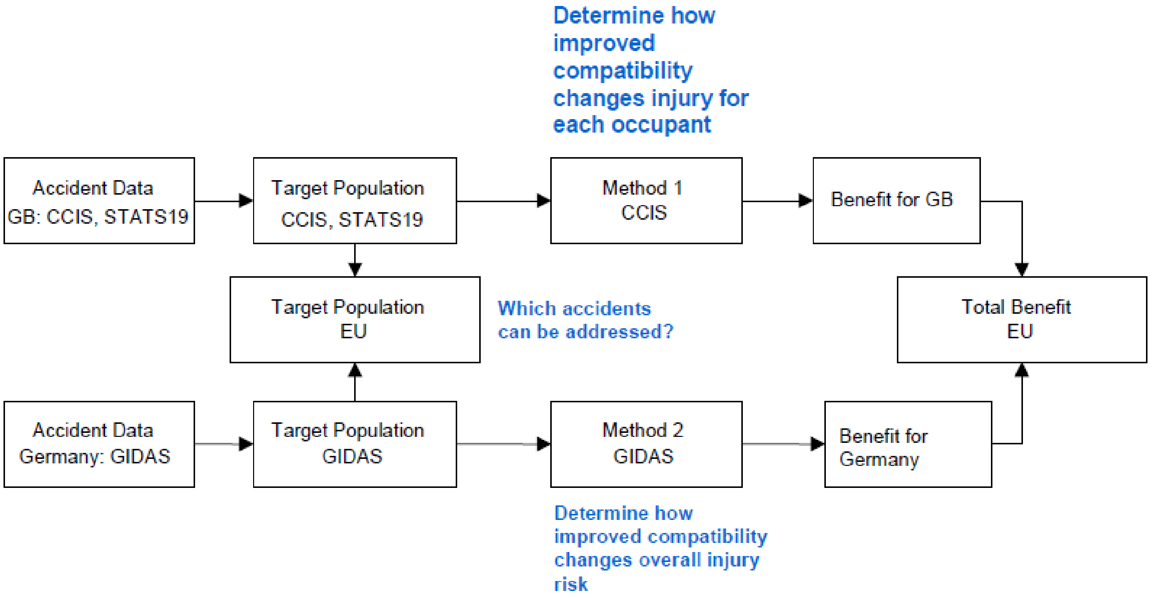

Figure 2.1: Accident and Benefit Analysis Approach in VC-Compat [Edwards 2007].

2.1 Informal Working Group on Frontal Impact (UNECE-WP29/GRSP)

France made a proposal to change the frontal impact legislation – Regulation 94 – within the UNECE framework of the 1958 agreement. This agreement applies to signatory countries that include the European Union. As part of the proposal, France presented accident statistics identifying the Severity Rate indicator (SR) and Mortality Rate indicator (MR) [Chauvel 2009]. These terms were used in an analysis of vehicle models where all accidents involving a specific make and model of vehicle were collected. These terms are defined as:

$$SR = \frac{(N_{Fatalities} + N_{Severe\ Injuries})}{(N_{Fatalities} + N_{Severe\ Injuries} + N_{Minor\ Injuries + N_{Not\ Injured}})}$$

$$MR = \frac{(N_{Fatalities})}{(N_{Fatalities} + N_{Severe\ Injuries} + N_{Minor\ Injuries + N_{Not\ Injured}})}$$

The concepts of Severity Ratio and Mortality Ratio were further developed to describe the self and partner protection level of a particular vehicle model as explained below. When the numerator is the number of casualties in the reference vehicle model and the denominator is the total injuries in the sample then the term reflects the self-protection of that vehicle model. It is the conditional probability of injury for an occupant of the reference model given a crash. Conversely, if the numerator is the number of casualties in vehicles struck by the reference vehicle, the aggressivity of the vehicle is quantified as the conditional probability of injury when struck by the reference vehicle in a crash. Two countries submitted information to the working group, France and Germany.

2.1.1 Informal Working Group on Frontal Impact: French Data

The analysis of the French national database (ONISR) was restricted to R94 compliant vehicles and required at least one police reported injury. Belted front seat occupants involved in frontal crashes were collected for the years 2005-2008. With the selection criteria approximately 1800 car-to-car crashes and 861 single vehicle crashes were identified [Chauvel 2009].

The French data showed a higher SR for smaller vehicles in car-to-car collisions although the results are not statistically significant. Similarly, heavier vehicles tended to be more aggressive to the collision partners. This is visualised in Figure 2.2. Ideally a car should have a balanced self and partner protection, indicated by the diagonal blue line. Vehicles above the line have better partner protection than self protection and cars below the line are the opposite [Chauvel 2009].

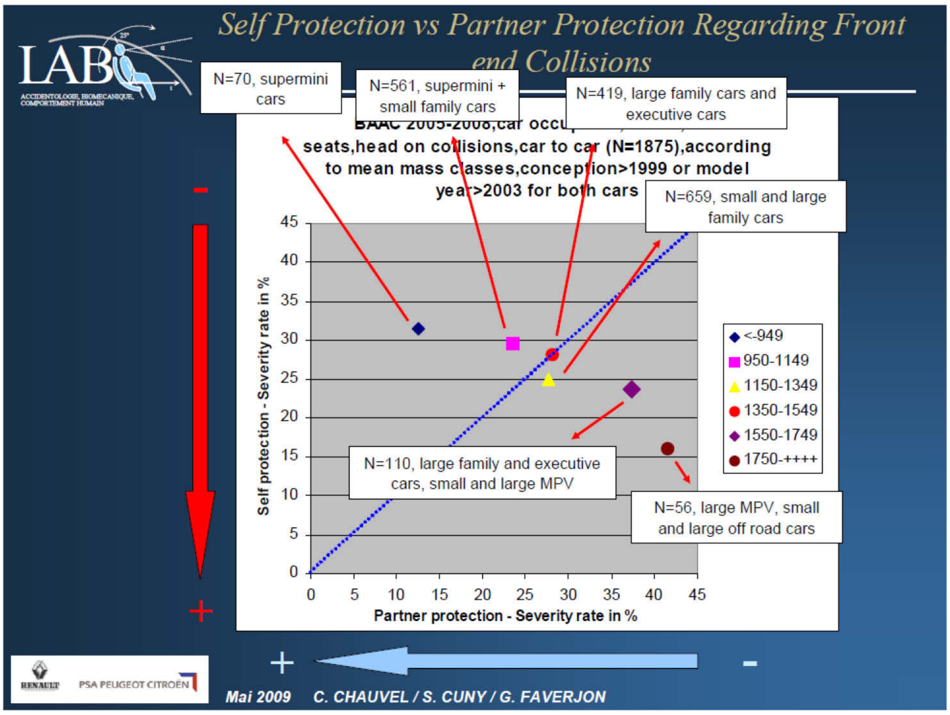

Figure 2.2: Self and partner protection data from France [Chauvel 2009].

The French analysis included an evaluation of vehicle safety in single vehicle collisions. It was shown that the injury risk was essentially identical for all vehicles contrary to the results for car-to-car crashes. The final stage in the analysis was an estimate of the benefit if a new frontal test procedure could harmonise the test severity so that it was less sensitive to mass. If the SR value for all vehicles could be harmonised to one value through improved test procedures, fatal and serious injuries in frontal impacts would be reduced by 40% in France [Chauvel 2009].

The data in Figure 2.2 provides information on the combined effect of mass, geometry, and vehicle architecture but does not identify the role of each of these parameters on compatibility.

2.1.2 Informal Working Group on Frontal Impact: German Data

Similar to the French contribution to the working group, BASt conducted an analysis of the German national statistics (police reports) to identify characteristics of the German accidents and performance of vehicles within the fleet [Pastor 2009/1; Pastor/2].

An analysis of the car-to-car accidents produced similar results to that in France, smaller vehicles had higher frequencies of injuries than larger vehicles. The German analysis further analysed the influence of the crash partner to establish the role of other vehicle parameters. A "matched pairs" analysis was used to establish a ranking of the relative safety of the different vehicles and quantify the relationships between the vehicle models. Through the analysis, different options for countermeasures were analysed:

a) Do nothing
b) Just add „crashworthiness" to small cars to reach high NCAP level
c) Increase „crashworthiness" of all cars to high NCAP level
d) Do nothing but adjust restraint system to female
e) Do nothing but adjust restraint system to female and elderly occupants
f) Better „crash energy distribution"

The results indicated that benefits became noteworthy after item d) on the list. In other words, just changing the self-protection of vehicles had little benefit unless it was combined with improvements to the restraint system to address non-standard occupants. Better crash energy distribution was also identified as a potential for improvement but it was difficult to identify a test method that produced this effect.

The analysis was further refined and it was noted that the collision partner was critical in determining the injury risks. In terms of frequency, smaller cars tend to hit smaller cars due to the distribution of vehicle masses in the fleet. There was a tendency for more serious injuries when smaller car collide with heavier cars. There was a slight overrepresentation of fatal injuries in small vehicles when colliding with large vehicles. The difference in mass between vehicles appeared to be less relevant than the sex and age of the person injured.

Single vehicle frontal crashes were the largest subgroup in the German data. The data was analysed to establish the importance of different variables such as vehicle age, occupant characteristics, accident location, etc. The first point of note (for single vehicle frontal crashes) was that there was no influence of vehicle mass on the injury risk. The most critical parameters linked to occupant casualty were the occupant age, vehicle age, and object struck. Interestingly, the newer vehicles were more likely than older vehicles to be involved in frontal impacts than side impacts which may be a result of ESC.

2.2 European Accident Analysis for DG-Enterprise

A substantial investigation of frontal accidents [Richards 2001] was conducted by TRL in conjunction with BASt and Lab to investigate GB, D, and FR data, respectively. The analysis was extensive, broken into 3 main tasks of

1) Taxonomy of frontal impacts
    a. National Data
    b. In-depth Data
2) Case Analysis of the Effectiveness of UNECE R94

3) Compatibility

The main conclusions of interest to FIMCAR in point 1) were that a substantial number (approximately 2/3) of fatalities and serious injuries could be addressed by improving Regulation 94. The frontal impact configuration that was most common was an offset impact with direct loading of one longitudinal which the Regulation 94 test represents. The second most common configuration involved direct loading of both longitudinal which is represented by a full width test. Impacts with light goods vehicles (LGV) were significant in all three countries and should be addressed in future safety regulations.

The national data from GB and Germany suggests that the casualties related to impacts with narrow objects are small (5-6% in GB and 10-16% in Germany) and suggests that a specialised pole impact would not address a substantial part of the total target population.

The cumulative collision severity distribution of the current accidents, expressed in EES/ETS, shows that only small gains in safety would be achieved if the current regulation test severity was increased to correspond to the Euro NCAP test severity.

As noted previously for the German analysis in the GRSP informal working group, the occupant age and sex are relevant issues with elderly people being overrepresented in the fatality statistics for lower severity impacts. Many female and elderly casualties are reported in the front seat passenger position.

The most serious injuries were connected to the thorax and many were related to loading by the restraint system. Cases with higher injury severities had many injuries attributed to contact with intruding structures. Chest injuries were more common for elderly occupants.

The activities addressed in Task 2) (a review of 48 fatally injured occupants in CCIS) was conducted to observe vehicle performance in the individual cases. In this sample, 17 fatalities were attributed to high impact severity (11 significantly higher than current test conditions). There were 13 occupants that were judged as vulnerable. There were 14 occupants associated with different types of compatibility issues where over/underride of different vehicle types was reported.

To evaluate the effectiveness of R94, 25 CCIS occupants were identified that experienced an impact type and severity represented in the regulation. For these occupants injury outcome was worse than expected compared to the injury risk measured by dummies in Euro NCAP tests when the vehicle’s structural performance was worse than that observed in Euro NCAP tests. Therefore, it was thought that the cause of the worse than expected injury outcome was that the structural performance of the vehicle was worse in the accident than in the Euro NCAP test, This in turn was thought could have been caused by poor structural interaction and / or a frontal force matching problem (i.e. a compatibility problem) in the accident.

2.3 European Union Projects THORAX/COVER

Parallel to FIMCAR, two ongoing projects are also investigating occupant safety with a focus on injury biomechanics and injury risk measurement and criteria. The COVER project (Coordination of Vehicle and Road Safety Initiatives) [Cover Project 2013] and the THORAX project (Thoracic injury assessment for improved vehicle safety) [Thorax Project 2013] provided their summarised findings in project deliverables [Carroll 2009/1] and [Carroll

2009/2]. The data looked at the types and causes of injuries to the thorax and provided information about the factors influencing injury risk. The data reviewed in COVER/THORAX was essentially the same sources as for the previously reports. TRL, BAST, and LAB reviewed injuries in frontal impacts with modern vehicles.

Some general observations were that females and people over 52 years old had a higher risk of torso injuries. German data suggested that people 150-180 cm tall and weighing 40-60 kg were statistically most likely to have AIS 1 torso injuries. Although the same trend was present, the results were not statistically significant at higher AIS levels. The seating position seemed to influence the injury risk as the front seat passenger (not driver) had the most severe injuries even when on the non-struck side of the vehicle. These occupants were also mostly female. Rear seat passengers also reported torso injuries as the most common injury and these occupants tended to be smaller and younger occupants. A comparison of AIS 3+ torso injuries observed in the accident data compared to the vehicle's performance in Euro NCAP showed that Euro NCAP test data overestimates the restraints system effectiveness with or without a force-limiting belt.

2.4 Summary External Findings

Previous and ongoing research external to FIMCAR identified safety issues in frontal crashes. Mass influences crash performance by influencing both acceleration and intrusion. There is always a higher delta-v (and thereby higher accelerations) in small cars when they strike larger vehicles. Larger cars and smaller cars also have different energy absorbing and force level management issues that can result in larger deformations and intrusions in smaller cars. The mass issues could not be easily separated in the reviewed research.

In two studies, the real world vehicle performance was lower than that predicted by standard tests. These differences could be related to structural interaction issues as well as occupant vulnerability.

All the data reflect a range of impact configurations where the amount of the frontal structure was in contact with the collision partner. The two most common accidents can be represented by a combination of full width and offset tests. Narrow object and small overlap crashes were observed but did not represent a more significant portion of the accidents or casualties.

The most relevant injury issue that is appearing in the accident data are thorax injures, particularly for female and older occupants. Improvements in the structural performance of the vehicle must be measured using an appropriate test device and a small female test dummy may be a good solution. New injury risk functions and modifications for older occupants are desirable but beyond the scope of FIMCAR.

Further accident analysis in FIMCAR should focus on the structural behaviour issues of cars, in particular identification of structural interaction issues as well as resolving the specific issues related to vehicle mass (acceleration or stiffness/force level) to further develop test procedures.

3 APPROACH

The following in-depth accident databases were used for this work to provide a European perspective:

- GB Cooperative Crash Injury Study (CCIS) analysed by TRL with support from Chalmers
- German In-Depth Accident Study (GIDAS) analysed by BASt
- Pan European Accident Database (PENDANT) analysed by Chalmers.

To ensure that the results were appropriate for use to identify compatibility issues in the current fleet and help develop changes to the current legislation (UNECE Regulation 94) as far as was possible only Regulation 94 compliant vehicles (or those with an equivalent safety level) were selected for this work. The legal situation for frontal impact type approval within the European Union is:

- Since 1 October 1998 the Frontal Impact Directive 96/79/EC (equivalent to Regulation 94) was mandated for type approval of new vehicle types within the European Union.
- Since 1 October 2003 an approval was mandated for the first registration of a vehicle.

As a result of 96/79/EC, all vehicles in the fleet registered since 1st October 2003 are Regulation 94 compliant and vehicles registered before this date may not be compliant. However, many vehicles registered between 1st Oct 1998 and 1st Oct 2003 may be compliant. In the accident data vehicle registration year information is available. Hence, this parameter was used to help select Regulation 94 compliant vehicles. The precise details of how this was achieved are given in following sections for each of the accident databases analysed.

Unfortunately, during the course of the work it was found that the PENDANT database did not contain a large enough number of appropriate cases to be able to provide statistically meaningful results. Hence, the remaining Chalmers effort was re-directed to analysis of the GB CCIS accident database.

4 DESCRIPTION OF ACCIDENT DATABASES

A description of the accident databases used for this work is given below.

4.1 Great Britain

4.1.1 STATS19 National Accident Statistics

STATS19 data is comprised of the details of road traffic accidents attended by the police in Great Britain. In theory the police are required to attend every road traffic accident that involves an injury and whilst on scene officers fill out a series of standard forms. Details of the nature of the accident, the location, a crude classification of injuries and the overall accident severity are all collected. Officers make a judgement, often without further information from hospitals, and record the severity of the injured casualties and the overall accident as 'slight', 'serious' or 'killed'. This data is then collected, collated and analysed by the UK Department for Transport (DfT).

STATS19 is, in principle, the national database in which all traffic accidents that result in injury to at least one person are recorded, although it is acknowledged that some injury accidents are missing from the database and a few non-injury accidents are included. The database primarily records information regarding where the accident took place, when the accident occurred, the conditions at the time and location of the accident, details of the vehicles involved and information about the casualties. Approximately 50 pieces of information are collected for each accident [Baghat 2009].

The severity of the casualties involved in the accident is assessed by the investigating police officer. Each casualty is recorded as being either slightly, seriously, or fatally injured. Fatal injury includes only casualties who died less than 30 days after the accident, not including suicides or death from natural causes. Serious injury includes casualties who were admitted to hospital as an in-patient. Slight injury includes minor cuts, bruises, and whiplash. The full definitions of these injury severities (and all other information recorded in STATS19) are given in the STATS20 document which accompanies the STATS19 form. These definitions are also available online at www.stats19.org.uk. Accidents that are recorded in STATS19 are summarised annually in the DfT "Reported Road Casualties Great Britain" (RRCGB) series.

4.1.2 CCIS Detailed Accident Database

The Co-operative Crash Injury Study (CCIS) collected in-depth real world crash data from 1983 to 2010. Vehicle examinations were undertaken at recovery garages several days after the collision. Car occupant injury information was collected from hospitals and questionnaires sent to survivors. Multi-disciplinary teams examined crashed vehicles and correlated their findings with the injuries the victims suffered to determine how the car occupants were injured. The objective of the study was to improve car crash performance by developing a scientific knowledge base, which has been used to identify the future priorities for vehicle safety design as changes take place.

Accidents were investigated according to a stratified sampling procedure, which favoured cars containing fatal or seriously injured occupants as defined by the British Government definitions of fatal, serious and slight. In order for an accident to be included in the study, a "newer" car must have been involved – one that was 7 years old or younger at the time of the accident. The stratified sampling procedure means that CCIS records a relatively large number of fatal and serious accidents, which are often the most interesting from an injury prevention point of view.

4.2 Germany - GIDAS

GIDAS (German In-Depth Accident Study) is the largest and most comprehensive in-depth road accident study in Germany. Since mid 1999, the GIDAS project investigates about 2000 accidents in the areas of Hanover and Dresden per year and records up to 3000 variables per crash. The project is supported by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT) [Otte 2003].

In GIDAS, road traffic accidents involving personal injury are investigated according to a statistical sampling process using the "on the scene" approach. That means, teams are called promptly after the occurrence of any kind of road traffic accidents with at least one injured person which occurred in determined time shifts. Along with this method, severe accidents are recorded slightly more frequently than accidents with lower injury severities and this is mainly caused by a lower notification rate or late information. In order to avoid such biases in the database and to approach regional and national representativeness, comparisons are made regularly with the official accident statistics and e.g. the investigation areas were chosen accordingly to the national road network and built-up areas.

The detailed documentation of the accidents is performed by survey teams consisting of specialised students, technical and medical staff. The data scope includes technical vehicle data, crash information, road design, active and passive safety systems, accident scene details and cause of the accident. Surveyed factors include impact contact points of passengers or vulnerable road users, environmental conditions, information on traffic control and other parties (road users) involved. Additionally, vehicles are measured more in detail, further medical information is gathered and an extensive crash reconstruction is performed.

4.3 Europe - PENDANT

Pan-European Co-ordinated Accident and Injury Databases (PENDANT) is an in-depth crash injury database using STAIRS [Vallet 1999] protocols enhanced with CARE data [European Commission 2013]. It contains data on 1100 accidents from 8 European countries (Table 1) including:

- Frontal impacts
- Side impacts
- Rollovers
- Rear impacts
- Non-struck side impacts
- Pedestrian crashes.

Table 1: Cases Collected by the PENDANT Teams

	Accident	Vehicle	Occupant	Pedestrian
Sweden	150	264	355	0
France	132	201	296	0
Germany	171	328	424	21
Austria	75	152	229	8
Netherlands	175	326	235	18
UK	200	290	445	2
Finland	80	126	153	6
Spain	127	197	232	13
Total	1110	1884	2369	68

The data was collected during the PENDANT project (2003-2006). Inclusion criteria were that at least one car in the accident was built after 1998 and at least one personal injury was attributed to the accident. A more detailed description of the database and its major findings can be found in Lenard *et al.* 2006 [Lenard 2006].

5 GB ACCIDENT ANALYSIS

The GB accident analysis used the CCIS accident database and was performed mainly by TRL. Chalmers helped to perform some of the detailed case analysis.

5.1 Approach

The GB analysis consisted of the following three steps:

- Select data set for analysis
  - Using appropriate selection criteria a data set was formed for the analysis ensuring that as far as was possible only Regulation 94 compliant vehicles (or those with an equivalent safety level) were included.
  - The main characteristics of this data set and an equivalent national (STATS19) data set were compared to quantify any biases in the CCIS data set. This was necessary to help ensure that the results of the compatibility analysis performed were interpreted correctly.
- Overall analysis
  - The detailed characteristics of the CCIS data set were investigated.
  - An analysis was performed to quantify the magnitude of compartment strength issue. The analysis determined the proportion of casualties for which there was significant compartment intrusion (defined as greater than 10 cm) and investigated the characteristics of the accidents in which these casualties were involved compared to casualties in accidents without intrusion.
  - A matched pair analysis was performed to investigate if the compartment strength issue quantified above was a bigger issue for lighter cars compared to heavier cars.
  - An additional analysis was performed to determine the nature of the casualty's injuries, the injury mechanisms and the relationship of the injury mechanism with intrusion.
- Detailed case analysis
  - A detailed case analysis was performed to quantify the nature and magnitude of structural interaction and frontal force matching problems.

5.2 Data Selection

The following criteria were used for the initial selection of the accident data set:

- Occupant in car (M1) or car derived van
- Car involved in 'significant' frontal impact without significant rollover
- Car registered in year 2000 onwards and UNECE Regulation 94 compliant (or equivalent safety level)
  - Note: Cars which met this age criterion were selected even if they impacted an older car in a car-to-car impact. However, for some parts of the analysis (e.g. matched pair analysis) an additional selection criterion that both cars must meet this age criterion was used.

To determine whether or not a car was Regulation 94 compliant the following steps were taken:

- Determine registration date of car

- For cars registered 1st Oct 2003 onwards then legislation mandates that it is compliant.
- For cars registered from 1st Jan 2000 to 1st Oct 2003 checks were made to determine safety level of vehicle. These checks included check of performance in Euro NCAP tests (if available) and checks when new models were introduced (if a car was sold after Oct. 2003 then it was assumed that the case vehicle was Regulation 94 compliant).

The distribution of casualties in the initial CCIS dataset by injury severity and impact partner is shown in Table 2. The characteristics of this CCIS data set and an equivalent STATS19 data set were compared to quantify any biases in the CCIS data set. This was necessary to help ensure that the results of the compatibility analysis performed were interpreted correctly. It was found that the CCIS data set has a higher proportion of HGV/bus impacts, a lower proportion of narrow object impacts and a bias towards older occupants (see Appendix A).

Table 2: Casualties in initial CCIS dataset by injury severity and impact partner.

	Fatal	**MAIS 2+ survived**	**MAIS 1**	***Total***
Car - Wide object	32	95	208	335
Car - Narrow object	4	42	100	146
Car - Car	30	309	974	1313
Car - Light Goods Vehicle	5	44	97	146
Car - HGV / PSV	22	56	87	165
Car - Other	0	3	7	10
Total	93	549	1473	2115

The following further selection criteria were used to select the final CCIS data set used for the compatibility analysis:

- Front seat adult (over 12 years old) occupants
- Belted occupants
- MAIS 2+ injured occupants (for some parts of the analysis)

The distribution of casualties in the final CCIS dataset by injury severity and impact partner is shown in Table 3.

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Table 3: Casualties in final CCIS dataset by injury severity and impact partner.

	Fatal	**MAIS 2+ survived**	**MAIS 1**	***Total***
Car - Wide object	9	50	117	176
Car - Narrow object	1	16	57	74
Car - Car	23	226	714	963
Car - Light Goods Vehicle	2	31	55	88
Car - HGV / PSV	13	39	61	113
Car - Other	0	3	7	10
Total	48	365	1,011	1,424

5.3 Overall Analysis

5.3.1 Data Set Characteristics

The characteristics of the CCIS dataset were analysed. The results are shown in Figure 5.1 to Figure 5.9. Some of the main findings of this analysis were that:

- A high proportion of the occupants were involved in crashes with an ETS less than 60 km/h (where ETS was known), although over 25% of the fatally injured occupants were in crashes with ETS greater than 60 km/h (Figure 5.1).
- There is a higher proportion of fatally injured occupants in the HGV / PSV impact partner group compared to other groups indicating the more injurious nature of HGV / PSV type impacts. There is also a slighter higher proportion of fatally injured occupants in the car to wide object impact partner group indicating the slightly more injurious nature of this type of impact. (Figure 5.2).
- A high proportion of fatal and MAIS 2+ survived injured occupants (30% of fatal and 40% of MAIS 2+ survived) were in crashes with a high frontal overlap (75-100%) (Figure 5.3).
- Although the occupants in the “Over 75” age group made up a low proportion of the occupants in the dataset, they were a high percentage of fatal and MAIS 2+ survived occupants compared to the other age groups, i.e. they were over-represented (Figure 5.5).

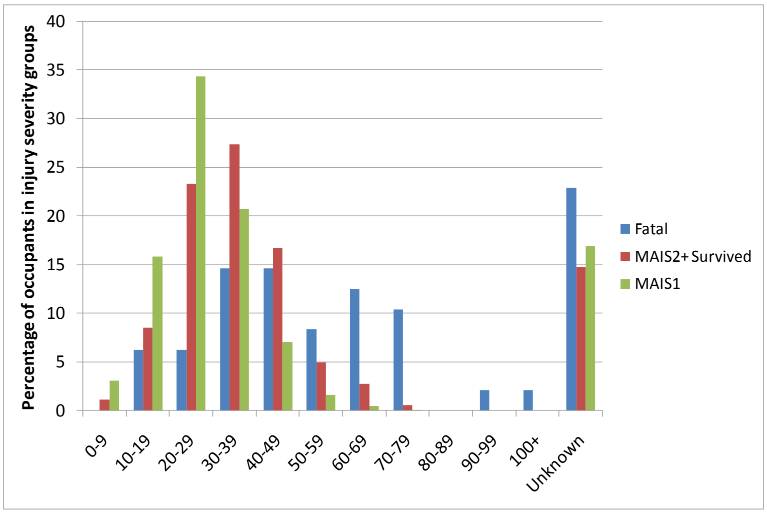


Figure 5.1: Percentage of occupants in injury severity groups against ETS (km/h).

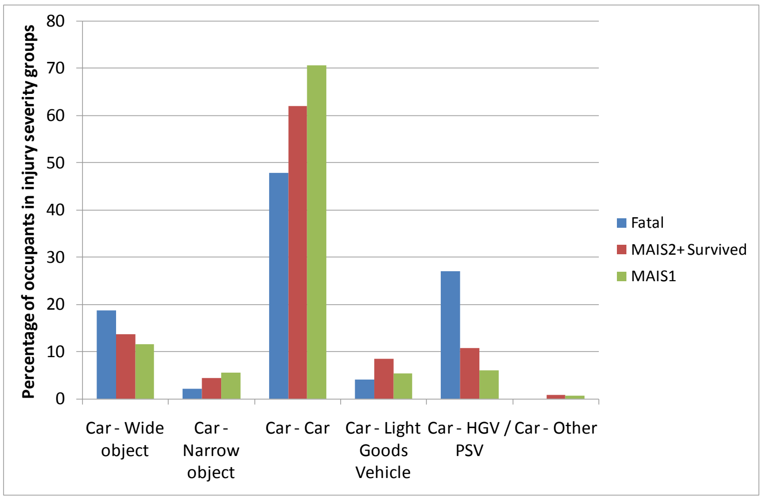


Figure 5.2: Percentage of occupants in injury severity groups against impact partner.

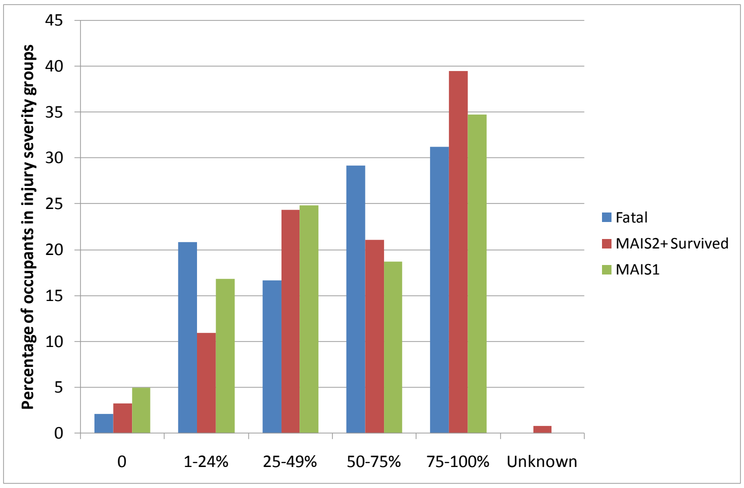


Figure 5.3: Percentage of occupants in injury severity groups against vehicle frontal overlap.

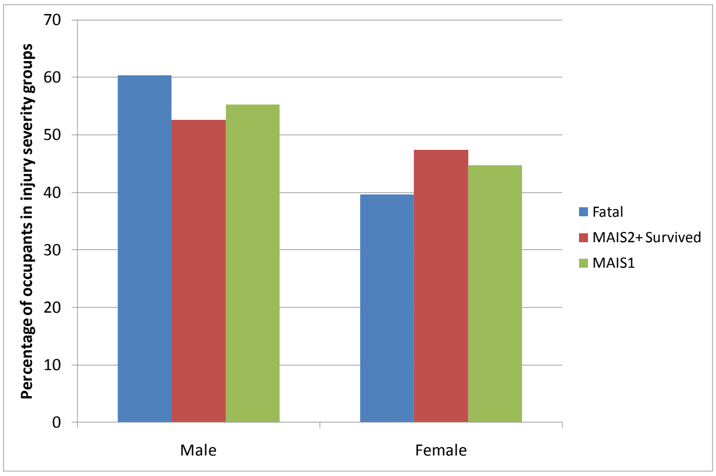


Figure 5.4: Percentage of occupants in injury severity groups by gender.

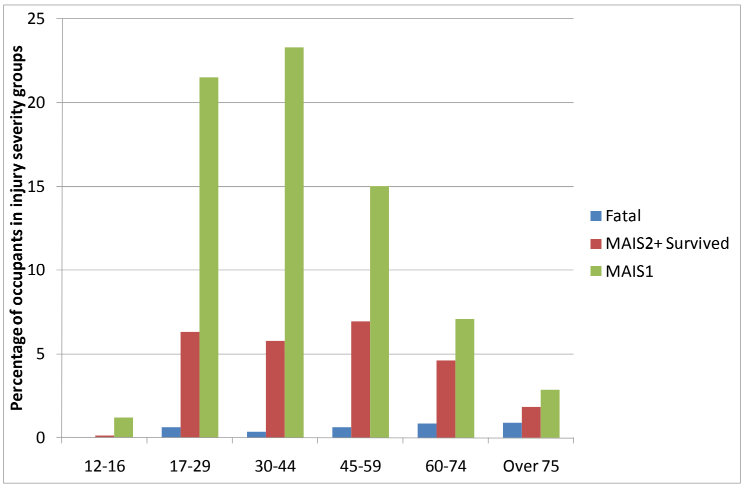


Figure 5.5: Percentage of occupants in injury severity groups against occupant age.

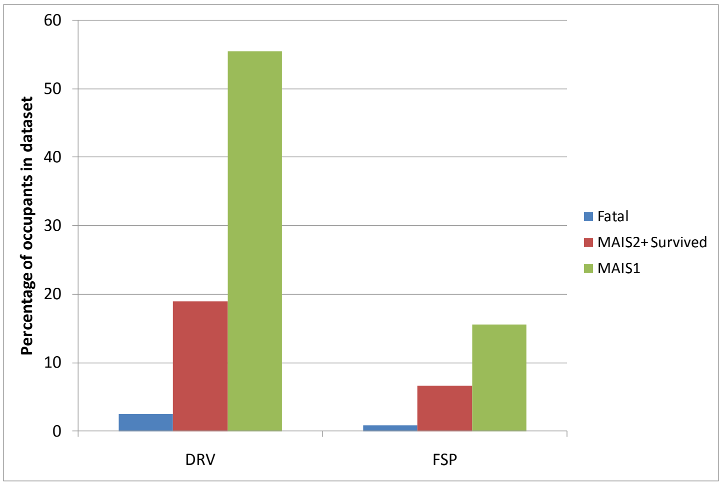


Figure 5.6: Percentage of occupants in injury severity groups against seating position.

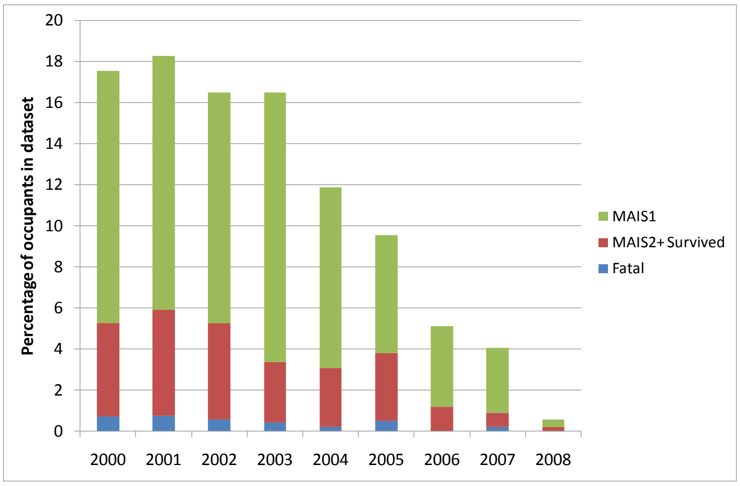


Figure 5.7: Percentage of occupants in injury severity groups against vehicle age.

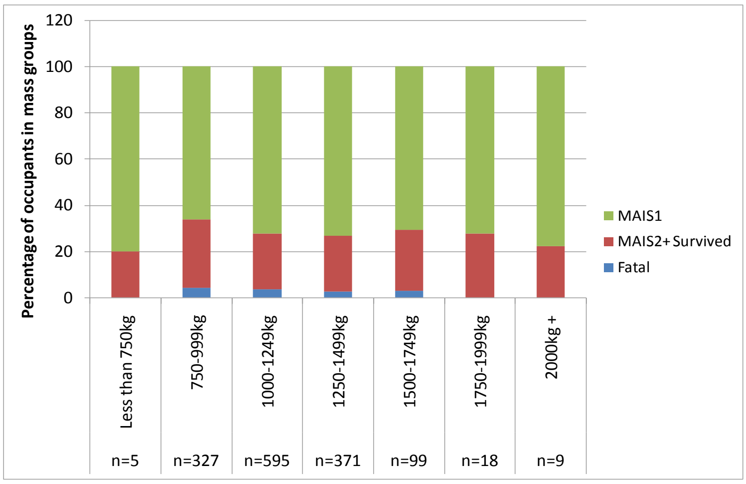


Figure 5.8: Percentage of occupants in injury severity groups against vehicle mass.

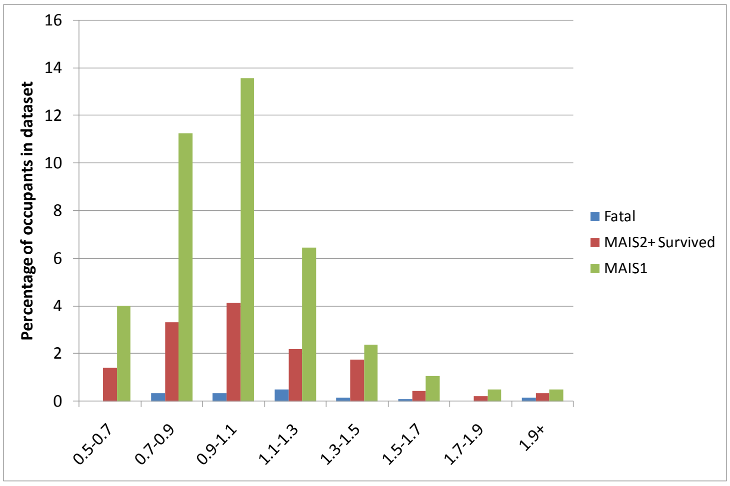


Figure 5.9: Percentage of occupants in injury severity groups against vehicle mass ratio – vehicle mass ratio less than 1.0 indicates that the partner vehicle is lighter.

5.3.2 Compartment Strength

For this analysis only MAIS 2+ injured occupants were considered.

In CCIS measurements of the vehicle interior are recorded in order to determine the reduction in available space for the occupant caused by intrusion. These measurements are taken at the footwell, knee contact areas on the facia/dashboard, and at the base of the windscreen/A-pillar. In addition, the reduction of the door aperture between the A and B-pillars is recorded.

For the purposes of this study to obtain an indication of the compartment strength issue it was determined whether an occupant had been exposed to intrusion or not. Small levels of intrusion of just a few centimetres were considered unlikely to have a significant effect on an occupant, and therefore intrusion was only considered to be present if a significant level was measured. It was decided that a vehicle would be considered to have sustained intrusion if there was at least 10 cm reduction in space recorded at any of the measurement points described above. In order to have had an effect on the occupant, this intrusion would have to have occurred on the same side of the vehicle as the occupant.

Using the methodology described above for determining if intrusion was present, the proportion of the occupants in the dataset who had intrusion present on their side of the vehicle was calculated (Table 4). This showed that approximately 56% of fatal occupants and 21% of MAIS 2+ survived occupants had intrusion present. Comparing across the different accident configurations showed that intrusion was present in approximately 25% of crashes with objects, cars and light goods vehicles, and in over 30% of crashes with HGVs and PSVs.

Table 4: Proportion of occupants in the dataset with intrusion present on their side of the vehicle.

	Fatal		MAIS 2+ survived		Overall	
	No. of occupants	**% of cases with intrusion**	**No. of occupants**	**% of cases with intrusion**	**No. of occupants**	**% of cases with intrusion**
Car - Wide object	9	55.6	50	20.0	59	25.4
Car - Narrow object	1	100.0	16	18.8	17	23.5
Car – Car	23	56.5	226	21.2	249	24.5
Car - Light Goods Vehicle	2	50.0	31	22.6	33	24.2
Car - HGV / PSV	13	53.8	39	23.1	52	30.7
Car - Other	0	0	3	0	3	0.0
Total	48	56.3	365	21.1	413	25.2

Further analysis of the dataset was undertaken to identify any factors which may have been a factor in the presence of intrusion. In particular, the ETS (Estimated Test Speed), frontal overlap, vehicle mass and mass ratio with the collision partner were investigated.

Analysis of the presence of intrusion with respect to ETS showed that the proportions of occupants in vehicles with intrusion increased as the ETS increased as shown in Figure 5.10. It was also observed that a high proportion of the cases with intrusion were observed for ETS less than 60 km/h.

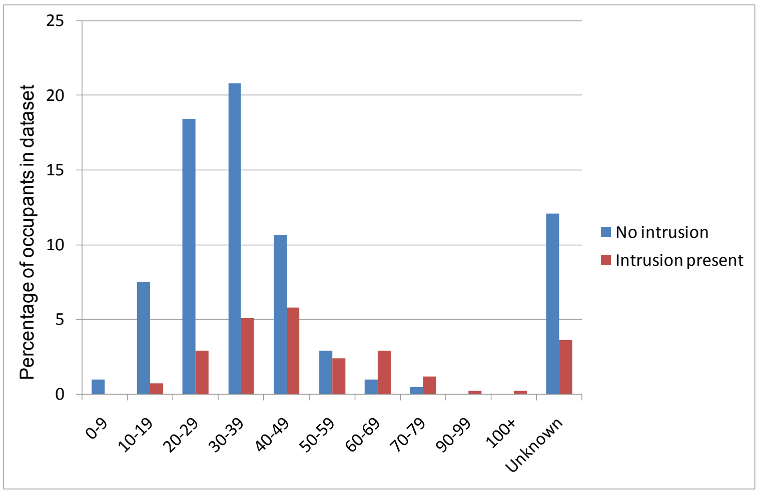


Figure 5.10: Percentage of occupants in dataset with and without intrusion against ETS (km/h).

Frontal overlap in CCIS is measured from one of the front corners of the vehicle. An overlap of "0" denotes that neither corner of the vehicle front was contacted (for example, a narrow impact between the longitudinal rails). Investigation of intrusion with respect to frontal overlap (Figure 5.11) showed that a lower proportion of cases with intrusion was present for crashes with a high frontal overlap (75-100 percent).

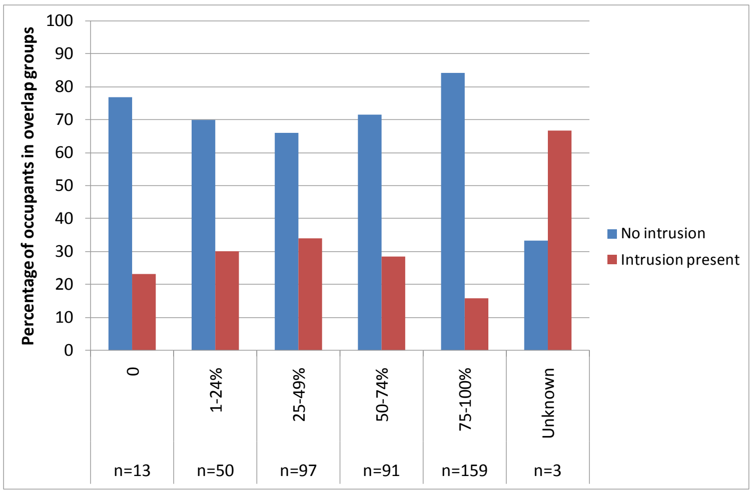


Figure 5.11: Percentage of occupants in dataset with and without intrusion against frontal overlap.

5.3.3 Matched Pair Analysis

To investigate issues related to mass ratio in car-to-car impacts a matched pair data set was used. This was necessary to ensure that the occupant injuries and performances of both cars in the impact were taken into account. The criteria used to select the matched pair data set from the initial CCIS data set described in Section 5.2 were:

- Front seat adult (over 12 years old) occupants
- Belted occupants
- MAIS 2+ injured occupants in at least one of the vehicles
- Both vehicles Regulation 94 compliant or equivalent

This resulted in a matched pair data set containing 34 accidents involving 68 vehicles. Only the driver injuries were considered in the following analysis.

Figure 5.12 shows the driver injury severity with mass ratio. A strong trend of an increase in driver injury severity with increasing mass ratio can be seen. This indicates that in a car-to-car impact the driver of the lighter car is more likely to sustain a more severe injury than the driver of the heavier car.

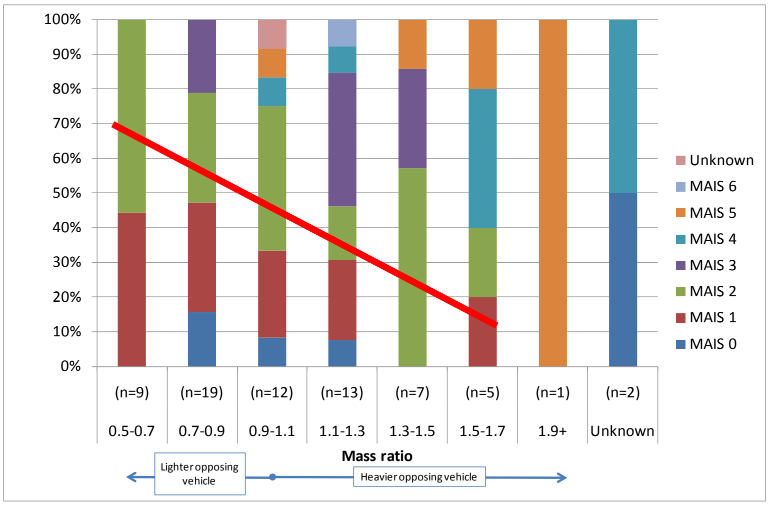


Figure 5.12: Driver injury severity with mass ratio.

This is in agreement with the results of previous studies such as the EC accident analysis for DG Enterprise which shows an increase in the aggressivity of vehicles with increasing mass from an analysis of French and German national data.

The main contributory factors to the increase in injury severity with increasing mass ratio have been described in previous analyses. They are:

- The increase in delta-v experienced by the occupants of the lighter car and associated increase in deceleration related injuries due to conservation of momentum.
- The higher likelihood of intrusion in the lighter car and associated increase in injuries related to intrusion.

If intrusion was the major and primary contributory factor, then one would expect to observe a similar trend of intrusion with mass ratio to that observed for driver injury severity with mass ratio. However, no such trend was observed (Figure 5.13). The implications of this are that intrusion is not the major contributory factor. However, it should be noted that the data sample used was relatively small and hence confidence in this result is limited. In addition, the result may be confounded by factors such as the age of the vehicle (newer vehicles generally have better compartment integrity) and the age of the occupant. A larger data sample would be needed to be able to remove these confounding factors.

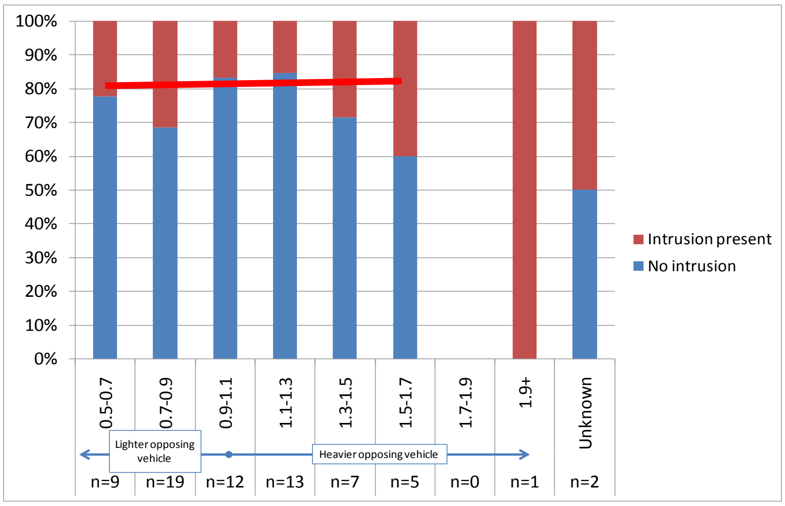


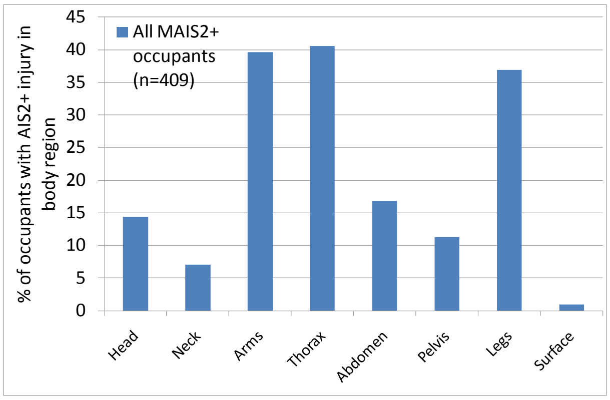
Figure 5.13: No intrusion / intrusion present with mass ratio.

5.3.4 Injury Patterns

An analysis of the specific injuries sustained by the vehicle occupants in the CCIS dataset was undertaken in order to understand if any patterns could be identified for injuries that were a particular issue in frontal impacts. In particular, the analysis of how injury patterns may be affected by the presence of intrusion was undertaken. Investigations into both the body injury distribution and the causation of the injuries were undertaken.

5.3.4.1 Injury Patterns and Intrusion

The distribution of the injuries relating to different body regions was undertaken. Only AIS 2+ injuries were taken into consideration for this analysis. This showed that over 80% of the fatal occupants in the dataset had sustained an AIS 2+ injury to the thorax, with approximately 65% sustaining AIS 2+ injury to the abdomen (Figure 5.14). Similar proportions of fatal occupants (approximately 55 percent) sustained AIS 2+ injuries to the head, arms and legs. For MAIS 2+ survived occupants, thorax injuries were also the most prevalent injuries alongside injuries to arms and legs. One possible reason for the high proportion of AIS 2+ arm injuries was that the shoulder was included in the arm body region, so injuries such as an AIS 2 fractured clavicle (collar bone) were included in the arm body region.



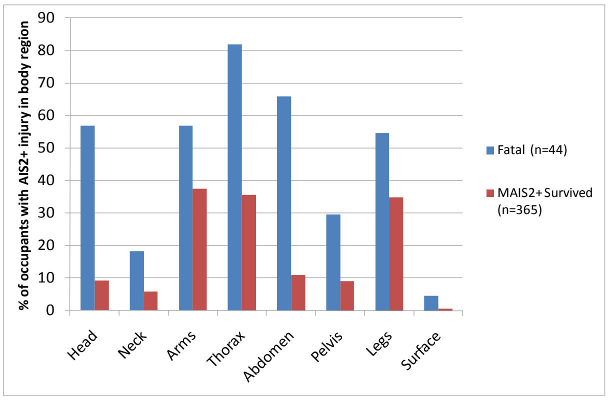


Figure 5.14: AIS 2+ body injury distribution, showing percentage of MAIS 2+ occupants sustaining an AIS 2+ injury in each of the body regions for all MAIS 2+ injured occupants and broken down for fatal and MAIS 2+ survived occupants.

Comparison of the occupant's body injury distribution in different accident types showed that a higher percentage of AIS 2+ head injuries occurred in car to heavy vehicle (HGV/PSV) crashes than other accident types, whilst leg, arm and thorax injuries appeared to be more prevalent in car to vehicle crashes than car to object crashes (Figure 5.15).

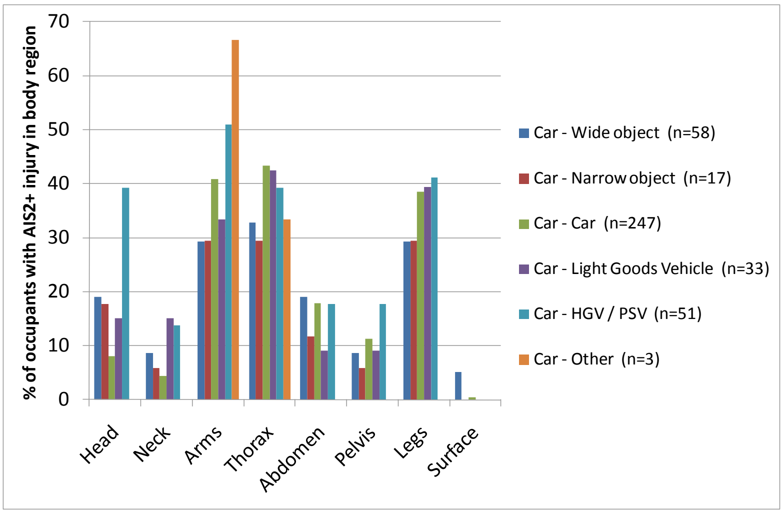


Figure 5.15: Body injury distribution for different accident types.

Analysis of the body injury distribution for the different occupant age groups showed that the percentage of occupants with AIS 2+ thorax injury increased substantially as occupant age increased, with approximately 25% of occupants under 44 years old sustaining AIS 2+ thorax injury compared to over 70% of occupants over 75 years old (Figure 5.16).

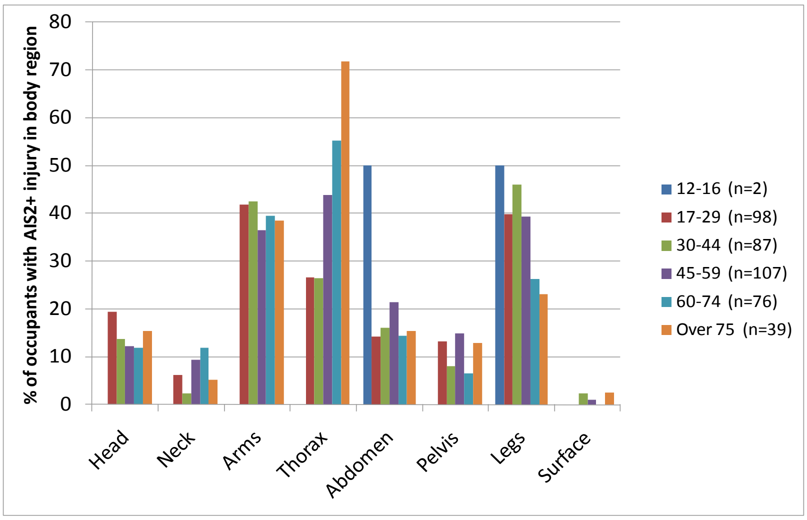


Figure 5.16: AIS 2+ body injury distribution for occupant age groups.

The comparison of body injury distribution for drivers and front seat passengers showed that drivers sustained a higher percentage of AIS 2+ leg and head injuries, most likely due to the presence of the steering wheel and pedals, whilst front seat passengers sustained a higher percentage of AIS 2+ abdomen and thorax injuries, possibly due to loading from the restraint system under deceleration (Figure 5.17).

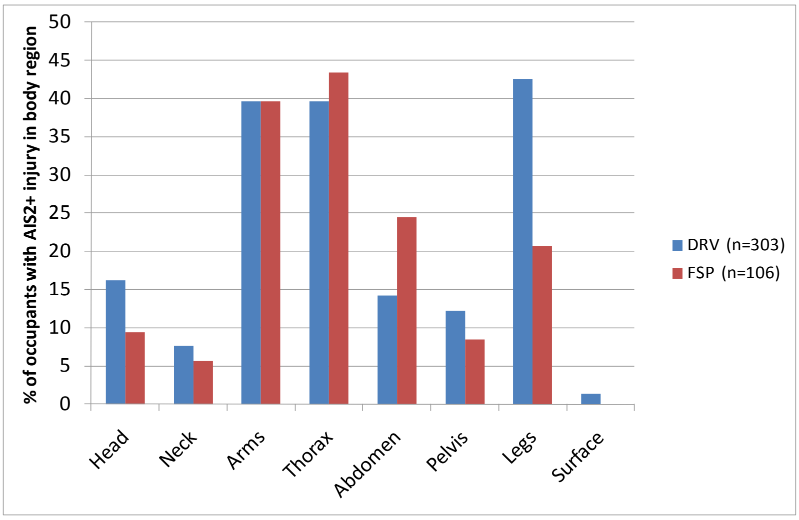


Figure 5.17: AIS 2+ body injury distribution for occupant seating position.

The body injury distribution appeared to be reasonably similar for male and female occupants, although male occupants sustained a slightly higher percentage of AIS 2+ head and leg injuries (Figure 5.18).

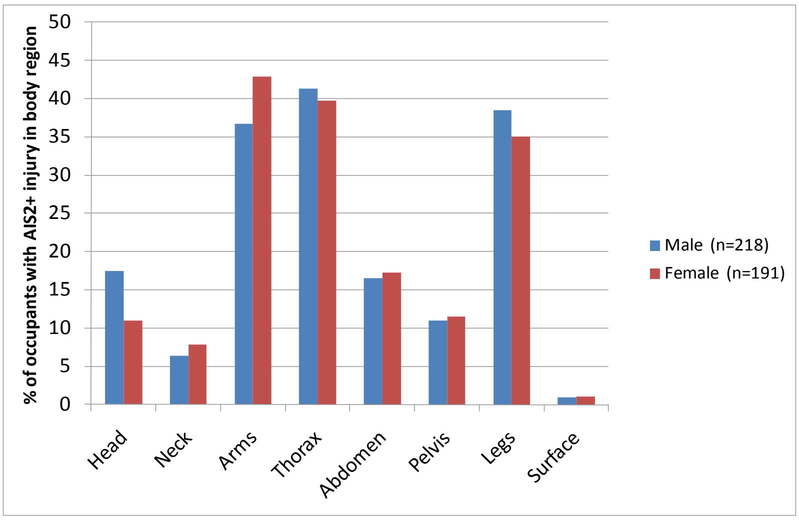


Figure 5.18: AIS 2+ body injury distribution for occupant gender.

The effect of intrusion into the occupant compartment on the injuries sustained by the occupants was investigated, which showed an increase in the percentage of occupants sustaining AIS 2+ injuries to all body regions in the presence of intrusion (Figure 5.19). This increase was most significant for the legs, where over 70% of MAIS 2+ occupants sustained AIS 2+ injuries when intrusion was present compared to just over 20% when no intrusion was recorded. Significant increases were also observed for the head, abdomen and arms, whilst only a slight increase was observed for thorax injuries.

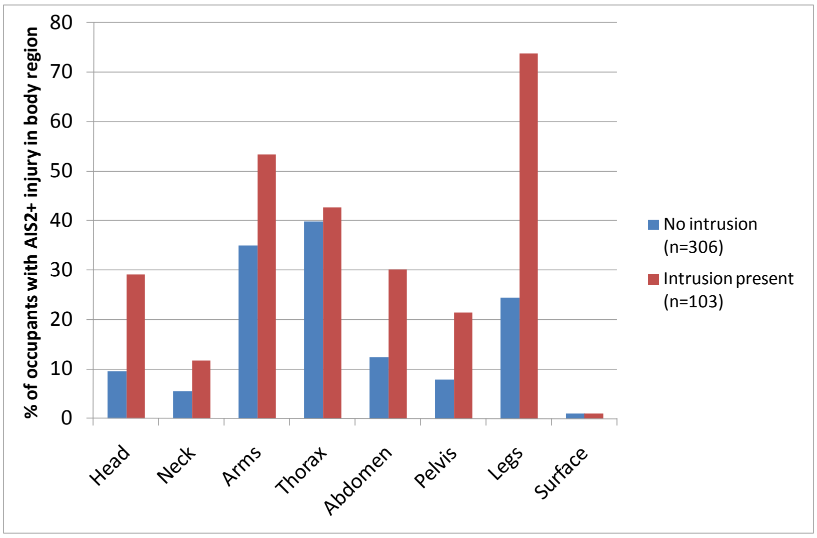


Figure 5.19: AIS 2+ body injury distribution for intrusion.

It was also observed that the presence of intrusion had a significant effect on the number of individual AIS 2+ injuries that the occupants sustained. Figure 5.20 shows how over 60% of MAIS 2+ occupants in vehicles where intrusion was not present only sustained a single AIS 2+ injury, with almost 90% sustaining 3 or fewer AIS 2+ injuries. Only approximately 16% of MAIS 2+ occupants in vehicles where intrusion was present sustained a single AIS 2+ injury, meaning that over 80% had sustained multiple AIS 2+ injuries.

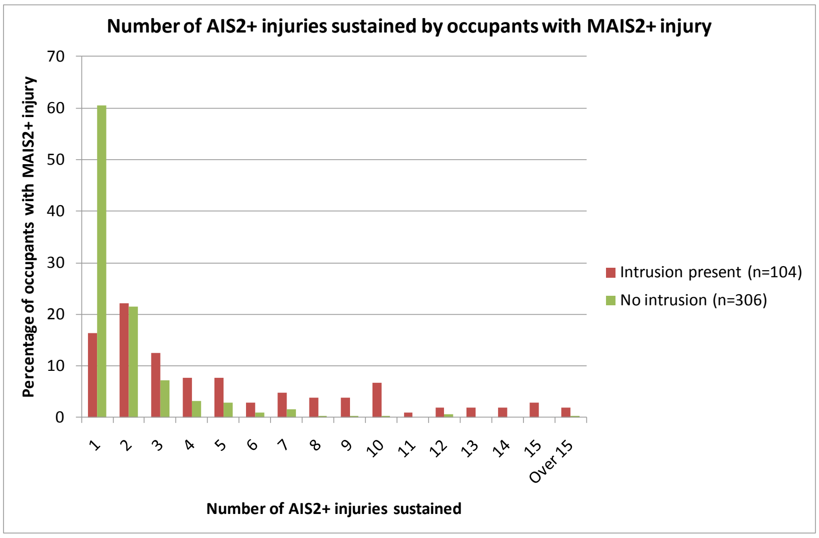


Figure 5.20: Number of AIS 2+ injuries sustained by MAIS 2+ occupants for intrusion.

This analysis indicated that the presence of intrusion into the occupant compartment corresponded with a significant increase in the number of AIS 2+ injuries sustained by the occupant in a crash. However, it must be remembered that the presence of intrusion is closely related to the severity of the accident as shown in Figure 5.10.

5.3.4.2 Injury Causation

In the CCIS database each injury is attributed a causation code depending on how the investigators had determined that the injury had been caused. For example, an occurrence of multiple rib fractures may have been attributed a causation code relating to the seat belt, whilst a fracture to the tibia or fibula may have been attributed to contact with the facia. In addition, the investigators also determined whether the injury causation directly related to contact with a component that had intruded into the compartment.

For the purposes of this investigation these causation codes were grouped into six general categories:

- “Restraint” – for causation codes relating to seat belts and airbags;
- “Contact No Intrusion” – for causation codes relating to contact with an interior component of the occupant’s vehicle which had been determined by the investigators as not having intruded into the compartment;
- “Contact Intrusion” – for causation codes relating to contact with an interior component of the occupant’s vehicle which had been determined by the investigators as having intruded into the compartment;
- “Non-Contact” – for injuries where no contact with any component was made (e.g. whiplash);
- “Unknown causation” – for injuries where the investigators could not determine the cause of the injury;
- “Other object” – for causation codes that related to contact with another object inside or outside the vehicle, such as unrestrained loads, an opposing vehicle or an external object such as a tree or lamppost.

It should be noted that the classification of 'restraint' injuries does not imply that there was a problem or issue with the restraint system that caused the injury, or that not using a restraint would have resulted in a reduction in injuries. These injuries were likely to have been due to the loading of the occupant from the restraint system during the deceleration of the vehicle, and therefore could also be described as 'acceleration loading' injuries.

The percentage of MAIS 2+ injured occupants in the dataset who sustained AIS 2+ injuries related to each causation category are shown in Figure 5.21. The labels on each of the columns in the graph show the actual number of occupants who sustained an AIS 2+ injury in each category. It should be noted that any occupant who sustained multiple AIS 2+ injuries with different causations was recorded once in each relevant causation category.

This analysis showed that just about 45% of all the MAIS 2+ injured occupants in the dataset sustained at least one AIS 2+ injury where the causation was the restraint system, which was the most prevalent injury causation category. Approximately 25% of the occupants sustained an AIS 2+ injury directly related to contact with intrusion. This reduced to 16% if vehicles with intrusion less than 10 cm were classified as having no intrusion.

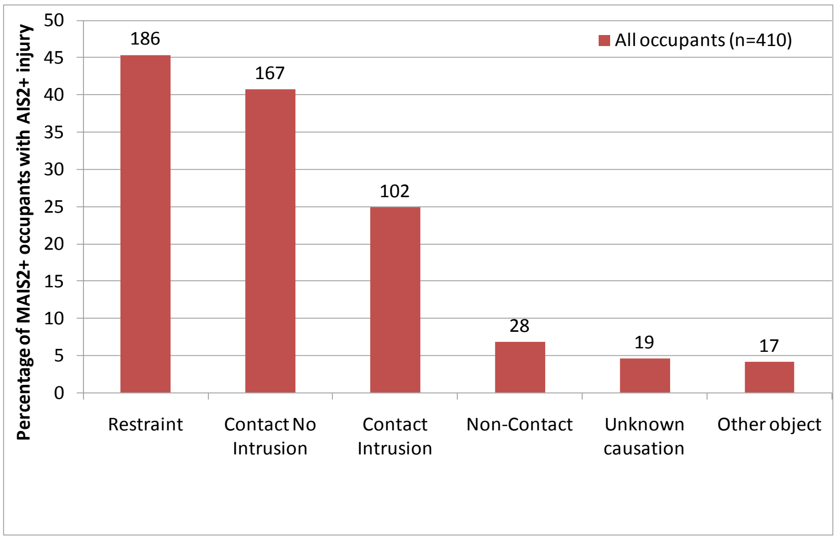


Figure 5.21: AIS 2+ injury causation for MAIS 2+ injured occupants in dataset.

When the injury causation was analysed with respect to intrusion, it was observed that approximately 65% of the MAIS 2+ occupants that were in a vehicle with intrusion sustained an AIS 2+ injury from contact with intrusion (Figure 5.22). However, it was also observed that between 35 and 40% of the occupants in vehicles with intrusion sustained AIS 2+ injuries in each of the causation categories relating to the restraints or contact with no intrusion.

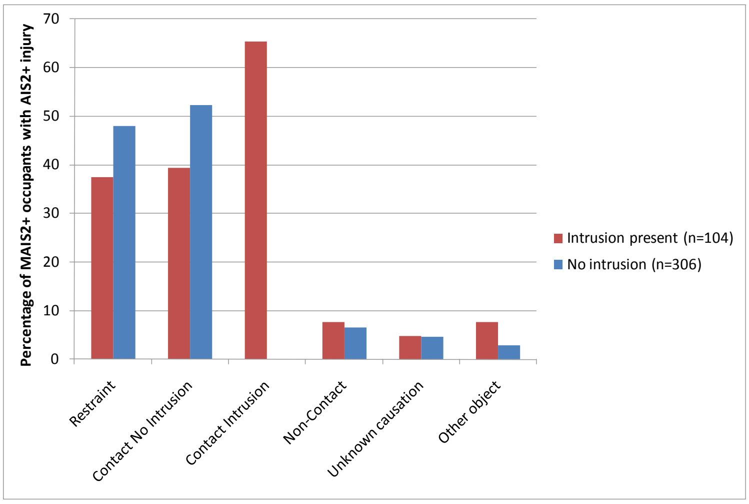


Figure 5.22: AIS 2+ injury causation for MAIS 2+ occupants in dataset with respect to intrusion.

Further analysis was performed to investigate the cause of the most severe injury received by the occupant. The purpose of this was to determine how relevant the injuries associated with 'contact with intrusion' were compared to the other injuries that the occupant had, i.e. is the injury associated with contact with intrusion generally the most severe injury the occupant has or does the occupant generally have another injury which is more severe.

When the cause of the most severe injury received by the MAIS 2+ injured occupants in the data set was analysed it was seen that the most severe injury was caused by 'contact with intrusion' for 22% of MAIS 2+ injured occupants (Figure 5.23). From the analysis above it was shown that 25% of occupants received an AIS 2+ injury caused by 'contact with intrusion'. Hence it can be concluded that if an occupant received an injury caused by contact with intrusion, in the majority of cases (88%) it was the most severe injury received by that occupant.

It should be noted that there are some duplicates in Figure 5.24 for occupants who received more than one most severe injury by more than one cause, e.g. an occupant who received an AIS 3 leg injury caused by contact with intrusion and an AIS 3 thorax injury caused by the restraint system. In the total sample, there were 38 (out of 409) duplicates.

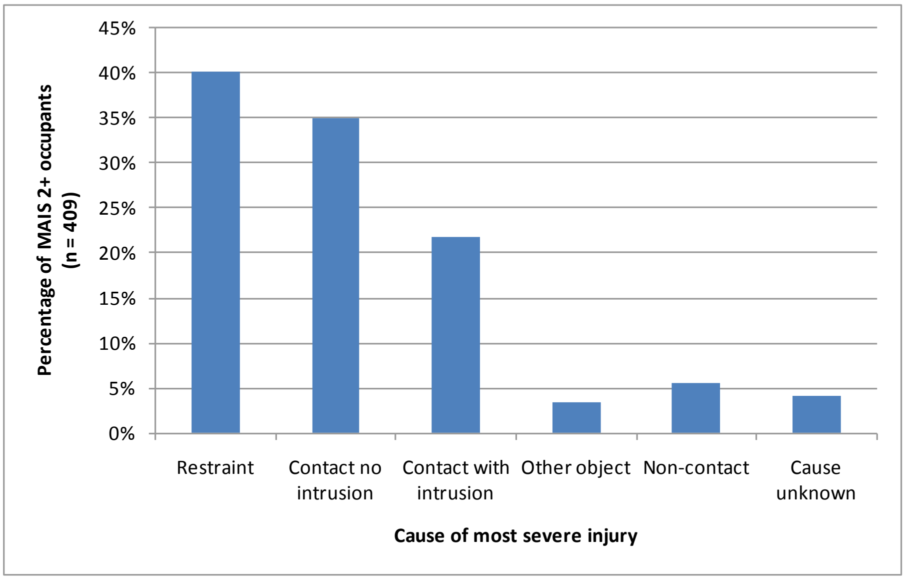


Figure 5.23: Cause of most severe injury for MAIS 2+ occupants in dataset.

If this graph is broken down into vehicles which had intrusion (defined as intrusion > 10 cm) and those that did not, it shows that even for vehicles which had intrusion in a significant number of cases (approx. 25%) the occupant's most severe injury was related to the 'restraint system'. It should be noted that some occupants in vehicles with no intrusion have injuries related to 'contact with intrusion'. The reason for this is that intrusion is defined as > 10 cm, so these vehicles will have had intrusion < 10 cm.

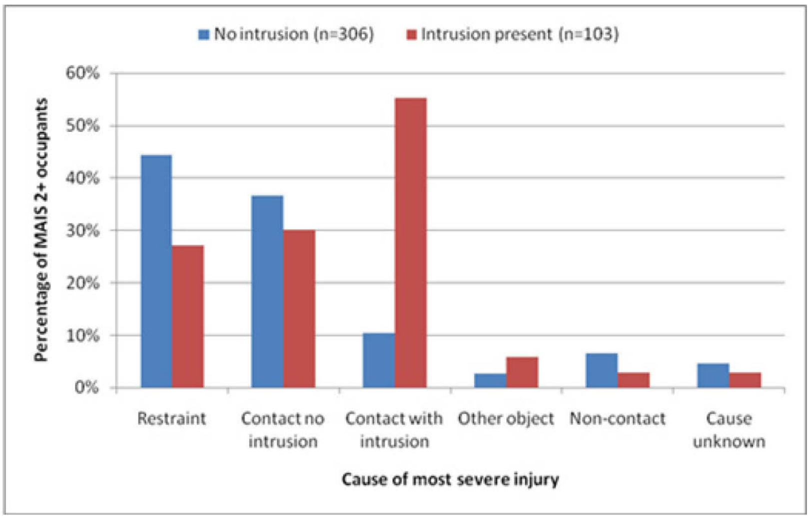


Figure 5.24: Cause of most severe injury for MAIS 2+ occupants in dataset broken down for vehicles where intrusion was present (defined as intrusion > 10cm) and not present.

Additional analysis selected injuries with specific causes and investigated what body region was injured. It was found that for occupants whose most severe injury was caused by 'contact with intrusion,' the injury was mainly to the legs (46%) with some to the thorax 30%) (Figure 5.25). For occupants whose 'most severe' injury was attributed to the 'restraint system', the injury was mainly to the thorax (62%) with some to the arms (21%) which were mostly clavicle fractures[3] (Figure 5.26). Similarly for occupants whose most severe injury was attributed to 'contact no intrusion' the injury was mainly to the legs (42%) with some to the arms (30%) and thorax (12%) (Figure 5.27).

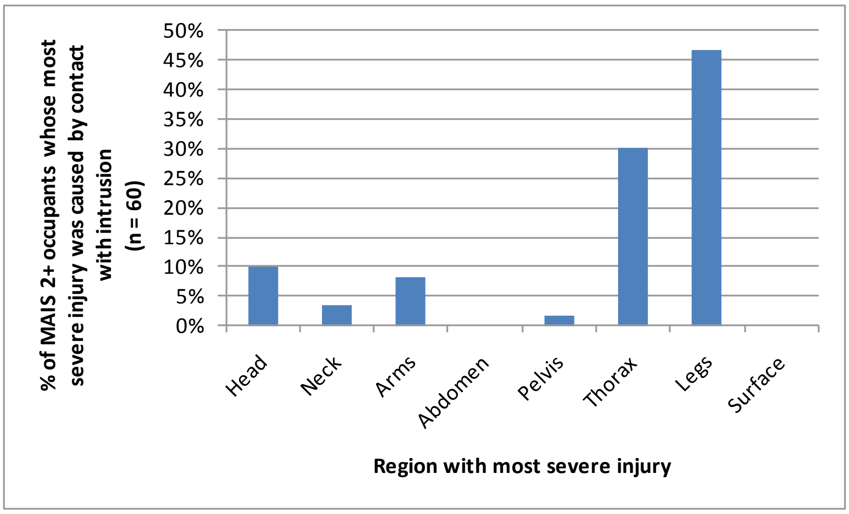


Figure 5.25: Distribution of 'most severe' injury by body region for MAIS 2+ belted occupants with their most severe injury caused by 'contact with intrusion'.

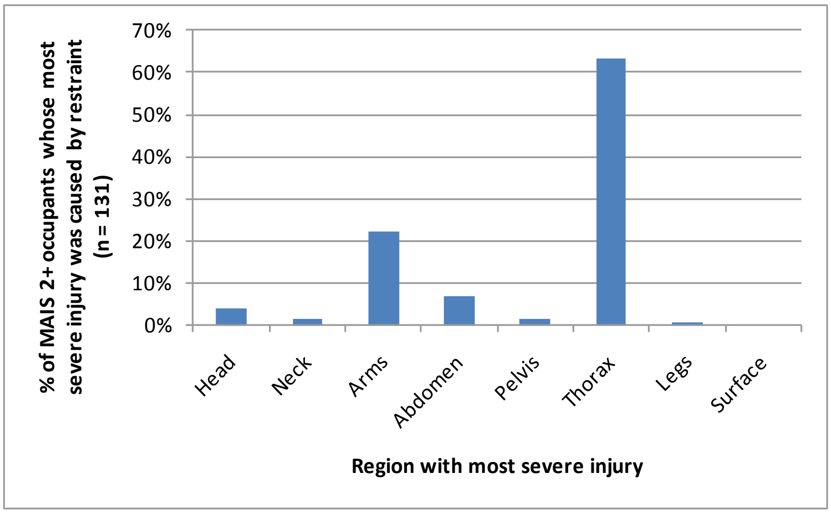


Figure 5.26: Distribution of 'most severe' injury by body region for MAIS 2+ belted occupants with their most severe injury related to the 'restraint system'.

[3] Please note:

- The clavicle is defined as part of the arm for the AIS classification.
- In general, clavicle fracture is related to seatbelt loading.

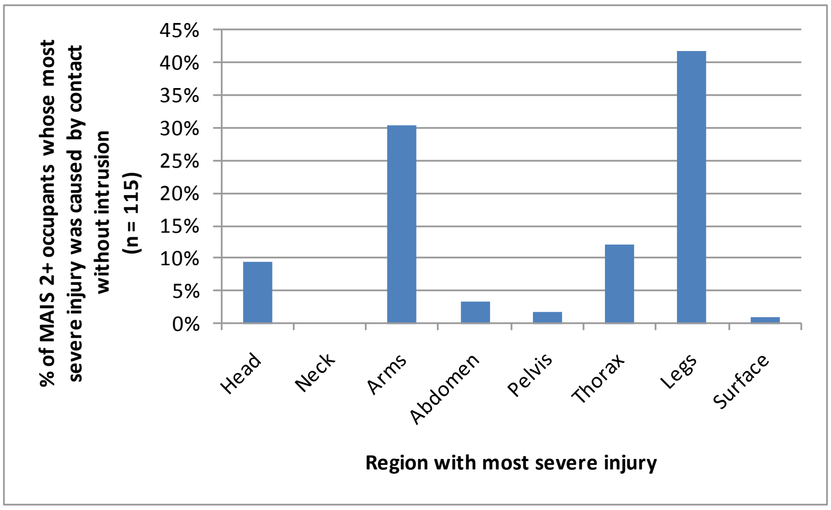


Figure 5.27: Distribution of 'most severe' injury by body region for MAIS 2+ belted occupants with their most severe injury caused by 'contact without intrusion'.

5.3.4.3 Investigation of Restraint Injuries

An additional data set was formed for this analysis which consisted of MAIS 2+ injured occupants who had an AIS 2+ injury caused by the restraint system. The characteristics of this data set were compared with full data set (i.e. all MAIS 2+ injured occupants) in the analysis below.

The distribution of AIS 2+ injuries by body region injured for MAIS 2+ occupants with an AIS 2+ injury caused by the restraint system was compared with the distribution for all MAIS 2+ injured occupants. This showed that 60% of MAIS 2+ occupants with restraint injuries sustained thorax injuries compared to 40% for all MAIS 2+ injured occupants (Figure 5.28). This indicates that the thorax injuries are related to the restraint system.

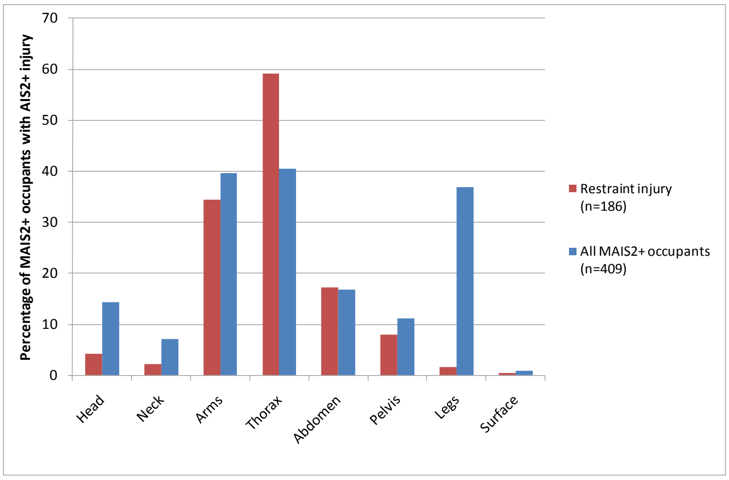


Figure 5.28: Comparison of distribution of MAIS 2+ occupants with restraint injuries with all MAIS 2+ occupants by body region injured.

A comparison of the distribution of MAIS 2+ injured occupants with restraint injuries and all MAIS 2+ injured occupants with overlap shows a higher proportion of the restraint group in higher overlaps (Figure 5.29). This indicates that in higher overlap impacts occupants are more likely to sustain a restraint related injury.

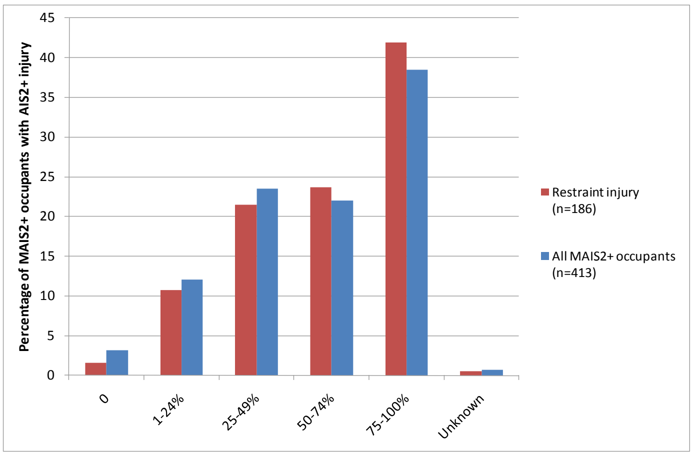


Figure 5.29: Comparison of distribution of MAIS 2+ occupants with restraint injuries with all MAIS 2+ occupants by overlap.

A comparison of the distribution with age of all MAIS 2+ injured occupants and MAIS 2+ injured occupants with restraint injuries shows a larger proportion of older occupants in the restraint injury group (Figure 5.30). This indicates that older occupants are more likely to sustain a restraint related injury.

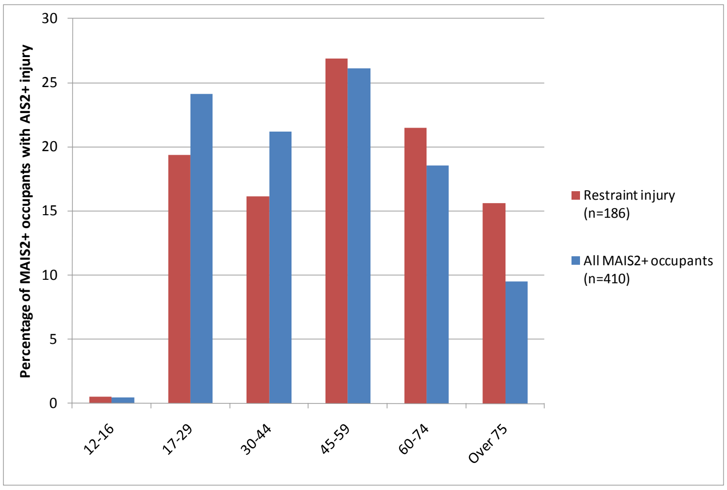


Figure 5.30: Comparison of distribution of MAIS 2+ occupants with restraint injuries with all MAIS 2+ occupants by age.

A comparison of the distribution with gender of all MAIS 2+ injured occupants and MAIS 2+ injured occupants with restraint injuries shows a slightly larger proportion of female occupants in the restraint injury group (Figure 5.31). This indicates that female occupants are slightly more likely to sustain a restraint related injury.

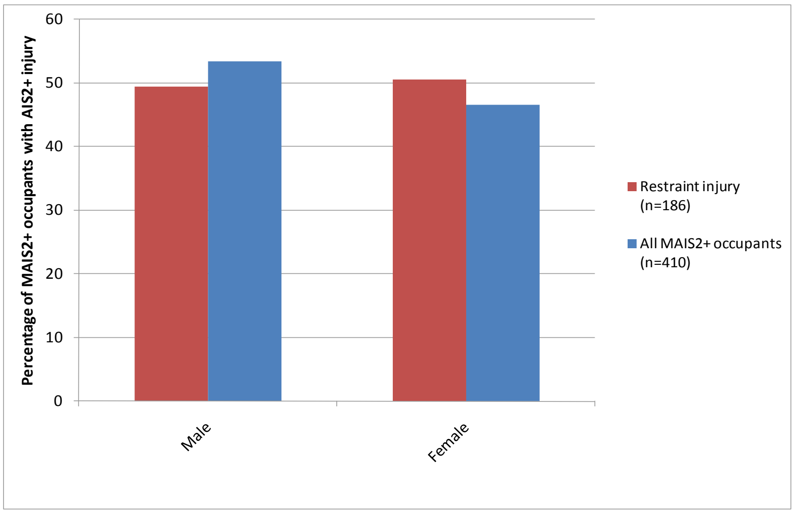


Figure 5.31: Comparison of distribution of MAIS 2+ occupants with restraint injuries with all MAIS 2+ occupants by gender.

A comparison of the distribution with seating position of all MAIS 2+ injured occupants and MAIS 2+ injured occupants with restraint injuries shows a slightly larger proportion of front seat passengers in the restraint injury group (Figure 5.32). This indicates that front seat passengers are slightly more likely to sustain a restraint related injury. This could possibly be because they are less likely to sustain a leg injury because there are no pedals on the passenger side.

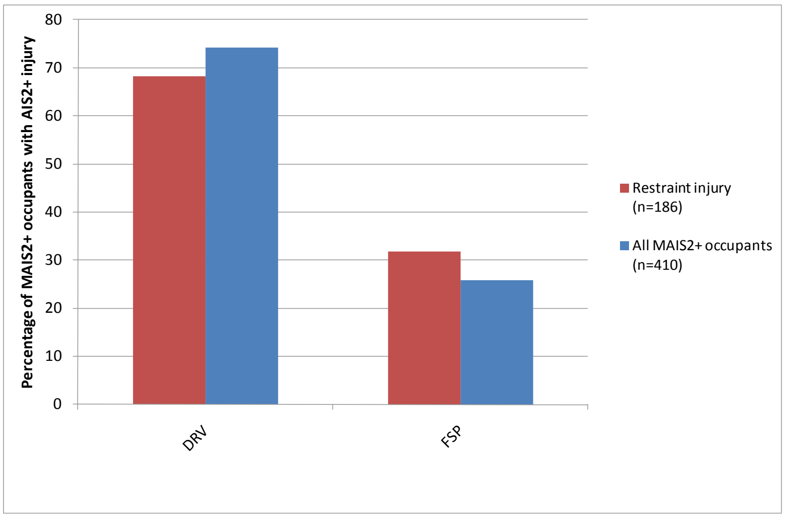


Figure 5.32: Comparison of distribution of MAIS 2+ occupants with restraint injuries with all MAIS 2+ occupants by seating position.

In summary the analysis shows that older people are more likely to sustain an AIS 2+ restraint related injury and these injuries are more likely to occur in higher overlap impacts. Also, female and front seat passengers are slightly more likely to sustain this type of injury and these injuries are more likely to be thorax injuries.

5.3.5 Conclusions CCIS Analysis

5.3.5.1 Data Set Characteristics

- A high proportion of fatal and MAIS 2+ survived injured occupants (30% of fatal and 40% of MAIS 2+ survived) were in crashes with a high frontal overlap (75-100%)
- Although the occupants in the "Over 75" age group made up a low proportion of the occupants in the dataset, they were a high percentage of fatal and MAIS 2+ survived occupants compared to the other age groups, i.e. they were over-represented
    - Occupants over 60 years old represent 18% of injured occupants, however account for 52% of fatalities and 25% of MAIS 2+ survived occupants
- There is a higher proportion of fatally injured occupants in the HGV / PSV impact partner group compared to other groups indicating the more injurious nature of HGV / PSV type impacts. There is also a slighter higher proportion of fatally injured occupants in the car to wide object impact partner group indicating the slightly more injurious nature of this type of impact.
- A high proportion of occupants were involved in crashes with an ETS less than 60 km/h, although over 25% of the fatally injured occupants were in crashes with ETS greater than 60 km/h.

5.3.5.2 Compartment Strength

- For MAIS 2+ injured occupants intrusion (> 10 cm) was present for 25% of them (56% of fatal occupants and 21% of MAIS 2+ survived occupants).
    - There was more intrusion present in impacts with HGVs / PSVs (30%) and smaller overlap impacts.
    - A high proportion of the cases with intrusion were observed for ETS less than 60 km/h.

5.3.5.3 Matched Pair Analysis

A strong trend of an increase in driver injury severity with increasing mass ratio was seen which indicates that in a car-to-car impact the driver of the lighter car is more likely to sustain a more severe injury than the driver of the heavier car. Possible contributory factors to this are the increased delta-v experienced by the driver of the lighter car and the increased likelihood of intrusion in the lighter car. No trend was observed in vehicle intrusion with increasing delta –v. The implications of this are that vehicle intrusion is not the major contributory factor and by default the increased delta –v experienced by the driver of the lighter car is. However, it should be noted that the data sample used was relatively small and hence confidence in this result is limited.

5.3.5.4 Injury Patterns

- AIS 2+ injuries to the thorax are the most prevalent. AIS 2+ injuries are also frequently sustained by the head, legs and arms
    - Over 80% fatally injured occupants and 35% MAIS 2+ survived occupants sustained AIS 2+ thorax injuries
- AIS 2+ thorax injuries appeared to be much more prevalent for older occupants compared to younger occupants.

  - 25% of occupants under 44 years old sustained AIS 2+ thorax injury compared to over 70% of occupants over 75 years old
- AIS 2+ head injuries were sustained by a significantly higher proportion of occupants in car to HGV impacts than in the other accident types.
- Drivers in the dataset were found to have a different pattern of AIS 2+ injuries compared to front seat passengers, with drivers experiencing more AIS 2+ injuries to the legs and head most likely due to contact with the facia/steering column or the steering wheel/airbag.
- AIS 2+ injuries resulting from deceleration loading of the occupant by the restraint system are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not
  - Over 40% MAIS 2+ occupants sustained AIS 2+ injury attributed to restraint loading
- For accidents for which intrusion was present, AIS 2+ injuries to the legs were the most prevalent
  - Where intrusion was present about 70% MAIS 2+ occupants sustained AIS 2+ leg injuries
  - Note: about 40% sustained AIS 2+ thorax injuries
- The investigation of intrusion with respect to occupant injuries showed that intrusion had a significant effect on AIS 2+ injuries sustained by the occupants. The proportion of occupants with AIS 2+ injuries in each of the body regions increased significantly when intrusion was present, although the smallest increase was observed for AIS 2+ thorax injuries. In addition, it was found that a significantly higher percentage of the MAIS 2+ injured occupants who were subjected to intrusion had multiple AIS 2+ injuries compared to those who were not subjected to intrusion. However, it must be remembered that the presence of intrusion is closely related to the severity of the accident.
- Analysis of injury mechanism found that 45% of MAIS 2+ injured occupants had an AIS 2+ injury related to the ‘restraint system’, 40% had an AIS 2+ injury caused by ‘contact with no intrusion’ and 25% had an AIS 2+ injury caused by ‘contact with intrusion’ In the majority of cases these injuries are the most serious injuries that the occupant had.
  - When the most severe injury was related to the ‘restraint system’ the injury was mainly to the thorax (62%) with some to the arms (21%) (mainly clavicle fractures).
  - When the most severe injury was related to ‘contact no intrusion’ the injury was mainly to the legs (42%) with some to the arms (30%) and thorax (12%).
  - When the most severe injury was related to the ‘contact with intrusion’ the injury was mainly to the legs (46%) and thorax (30%).
- AIS 2+ injuries resulting from contact with the intrusion occur in a large proportion of cases where compartment intrusion is present. In the majority of cases (over 80%) this injury is the most severe injury received by the occupant.
  - 65% of MAIS 2+ injured occupants in cars with intrusion greater than 10 cm sustained AIS 2+ injury attributed to contact with intrusion
  - 25% of all MAIS 2+ injured occupants received an AIS 2+ injury attributed to contact with intrusion. Note: this includes cases where the vehicle intrusion was less than 10 cm. If these cases are excluded the percentage reduces from 25% to 16%.

- The analysis of MAIS 2+ injured occupants with restraint related injuries compared to all MAIS 2+ injured occupants found that:
  - There was a larger proportion of older people in the restraint related injury group indicating a greater prevalence of this type of injury for older people.
  - There was a larger proportion of higher overlap impacts in the restraint related injury group indicating a greater prevalence of this type of injury in high overlap impacts.
  - There was a slightly larger proportion of female and front seat passengers in the restraint related injury group although this could be at least partially caused by the larger number of female front seat passengers.

5.4 Detailed Case Analysis

Compatibility is a complex issue but, as mentioned previously, can be broken down into three subtopics: structural interaction, frontal force levels and compartment strength. Structural interaction is a measurement of how well vehicles interact in frontal impacts. If the structural interaction is poor, the energy absorbing front structures of the vehicle may not function as designed leading to a risk of compartment intrusion at lower than designed impact severities. In general, frontal force levels are currently related to vehicle mass. As a consequence, small vehicles absorb more than their share of the impact energy as they are unable to deform the heavier vehicle at the higher force levels required. Compartment strength is closely related to frontal force levels but is nevertheless distinguished since it is such an important issue for self-protection. Matched frontal force and compartment strength levels would ensure that both vehicles in an impact absorb their share of the kinetic energy without compartment intrusion in either vehicle. This would reduce the risk of injury for the occupant in the lighter vehicle.

In order to understand whether compatibility issues such as structural interaction and frontal force / compartment strength matching were still present in the current vehicle fleet, a detailed case analysis was necessary. This was because these types of compatibility problems can only be identified through a detailed analysis which includes examination of photographic evidence of both vehicles.

5.4.1 Approach

The analysis was performed at an occupant level, i.e. each occupant was considered separately as opposed to each accident.

The analysis was divided into two parts, an analysis of fatal cases and an analysis of MAIS 2+ survived cases.

For each part of the analysis, cases were divided into ones where intrusion was present and ones where intrusion was not present. The reasons for this were:

- For the investigation of structural interaction it was only for the cases where intrusion was present that it could be determined definitely that poor structural interaction was directly linked to the injuries. This is because there are two consequences to poor structural interaction. The first is a decrease in the energy absorbing capability of the vehicle’s frontal structures because the vehicle’s structures are not loaded and hence do not collapse in the designed manner. The second is a change to the deceleration pulse of the vehicles passenger compartment which generally becomes more back loaded with a longer ride-down distance. Hence, in the cases where there was poor structural interaction and intrusion it could be assumed that improving the structural interaction would improve the energy absorption capability of the vehicle's front structures which in turn would reduce the intrusion. It was assumed that this would be beneficial for the occupant's safety. However, in the cases where there was poor structural interaction and no intrusion it could be assumed that improved structural interaction would alter the vehicle's deceleration pulse but it could not be determined definitely whether or not this would be beneficial for the occupant's safety.

- For the investigation of frontal force / compartment strength matching it was only for the cases where there was intrusion present in at least one vehicle that it could be determined definitely whether or not a problem was present. This is because for cases with no intrusion in either vehicle it is known that the vehicles have absorbed the impact energy in their frontal structures. Hence the frontal force and compartment strength levels are matched adequately at least for that particular accident case.

Intrusion present was defined previously, i.e. greater than 10 cm of intrusion measured at any of the following points; footwell, knee contact areas on the facia/dashboard, the base of the windscreen/A-pillar and reduction of the door aperture between the A and B-pillars greater than 10 cm. It should be noted that because the analysis was performed at an occupant level, the presence of intrusion was defined on the basis of the intrusion measured on the injured occupant's side of the vehicle (i.e. intrusion in the vicinity of the occupant). As a result, if there was over 10 cm of intrusion on the nearside of the car but less than 10 cm intrusion on the offside where the occupant was seated, then the case would be categorised as no intrusion present.

For each injured occupant the related accident was studied in detail. This included the assessment of the photographic records from each case, the intrusion levels present in each vehicle and the overall accident configuration (including ETS, vehicle mass, mass ratio, etc.) in order to determine whether one of the compatibility issues was present or not, i.e. structural interaction or frontal force and/or compartment strength matching.

Three types of structural interaction issue were identified:

- Over/underride
    - This is caused by the main rails of one vehicle riding over or under the main rails of the other vehicle. It can be the result of misalignment of a vehicle's main structures and / or poor stability of them. A classic example is the high structures of an SUV overriding the lower structures of a car. The distinguishing features of over/underride are the deformation and / or compartment intrusion profiles of the vehicles. Its presence can be identified from high deformation above the main rails and lower deformation below the rails on one vehicle and vice-versa on the other vehicle. Often the intrusion profile of the occupant compartment reflects this as well, e.g. higher deformation at the waist rail level and lower deformation at sill level on one vehicle and vice-versa on the other vehicle.

- Fork effect
    - This is caused by the bumper beam and other cross car structures being too weak to spread the load from the rails. The consequence of this is that these structures deform a lot or break which in turn allows the rail of one car to penetrate into the structure of the other car. This results in the crash loads not being transmitted into the car in the designed manner which in turn results in a decrease in the energy absorption capability of the car's frontal structures. The distinguishing features of the fork effect are large local deformations and/or breaking of the bumper beam and other cross car structures.
- Low overlap
    - This is caused by the overlap of the impact being so low that the main rails of the vehicles do not overlap and hence do not form a main load path in the crash. This results in greater loading of the vehicle's side structures through load paths such as the wheel to sill and sometimes direct loading of the A-pillar footwell area of one vehicle by the rails and bumper crossbeam of the other vehicle. The consequence of this is often high compartment intrusion in one or both cars. The distinguishing features of low overlap are little deformation of the main rail structures and large deformations of the vehicles side structures.

As mentioned above frontal force and/or compartment strength matching issues in car-to-car crashes could only be identified when there was intrusion in at least one of the vehicles. The distinguishing feature used to identify the issue was a large difference in the intrusion levels of the two vehicles involved in the accident. This could be no intrusion in one vehicle and over 10 cm intrusion in the other vehicle or 10 cm of intrusion in one vehicle and 30 cm of intrusion in the other vehicle. In car-to-object impacts only compartment strength issues could be identified. The distinguishing feature used to identify these issues was intrusion in a low severity impact.

It should be noted that frontal force and/or compartment strength problems were only identified in cases where no structural interaction problem was identified. This is because it was known that the structural interaction problem would have at least being a contributory factor to the frontal force and/or compartment strength problem but it could not be determined whether or not it was the main factor. Hence to avoid possible double counting of problems it was decided to only count frontal force / compartment strength problems when structural interaction problems were not present. This approach does have the problem that it may underestimate the degree of the frontal force / compartment strength problem.

To help the reader understand better the approach taken to identify compatibility problems, examples of cases in which compatibility issues were identified are given in the 'Results' sections below.

It should be noted that for some cases it was not possible to identify whether or not a compatibility issue was present because any evidence of it was masked by high vehicle deformation resulting from the high severity of the accident. These cases were categorised as high severity.

5.4.2 Data Sample

The initial dataset to be used for this analysis was as described in Section 5.2, as had been used for the previous analyses. As mentioned above, the analysis was undertaken in two parts. First, the cases where an occupant was fatally injured were investigated for all accident types, giving 48 occupants (Table 5). There were a total of 45 accidents in this dataset, as there were two fatalities in three of the accidents (two in car to HGV cases and one in a car-to-car case).

Table 5: Analysis group for detailed case analysis of fatally injured occupants

	Fatal
Car - Wide object	9
Car - Narrow object	1
Car – Car	23
Car - Light Goods Vehicle	2
Car - HGV / PSV	13
Car – Other	0
Total	*48*

After this analysis, a further investigation of crashes was undertaken involving MAIS 2+ survived occupants in car-to-car and car-to-object crashes. However, in the original dataset there were 226 occupants in car-to-car crashes and 66 in car-to-object crashes, which was too many to analyse on a case-by-case basis. In addition, the car-to-car crashes in the dataset contained collisions with older, non-R94 compliant, cars and crashes in configurations that were not frontal to frontal. Therefore only those car-to-car crashes where both vehicles were R94 compliant and the impact configuration was frontal to frontal were analysed in detail. This gave an analysis group of 104 occupants as shown in Table 6. Due to the presence of multiple MAIS 2+ survived occupants in some crashes, this related to 42 car to wide object crashes, 18 car to narrow object crashes and 33 car-to-car crashes.

Table 6: Analysis group for detailed case analysis of MAIS 2+ survived occupants

	MAIS 2+ survived
Car - Wide object	48
Car - Narrow object	18
Car - Car (Front-Front) Both R94 compliant	38
Total	*104*

5.4.3 Results: Fatal Case Analysis

Each of the accident cases containing the 48 fatally injured occupants was investigated. The results of the analysis showed that, out of the 48 fatal occupants (in 45 vehicles), 28 occupants (56%) had intrusion present on their side of the vehicle. These 28 occupants were in 28 vehicles, meaning that just over 60% of the vehicles containing fatally injured occupants sustained intrusion.

Further analysis identified structural interaction problems in 19 out of 48 cases (40%) as shown in Figure 5.33. However, it is only in 12 of these cases where there was intrusion (25%) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. Seven of these cases were over/underride and 5 were low overlap. Frontal force / compartment strength problems were identified in 4 cases (8%) which indicate that this is much less of an issue than structural interaction. However, it should be noted that poor structural interaction may mask frontal force / compartment strength matching problems. It is interesting to note the high proportion of high severity cases (11 cases 23%) for which the vehicle's deformation was so great that it masked any compatibility issue that may have been present.

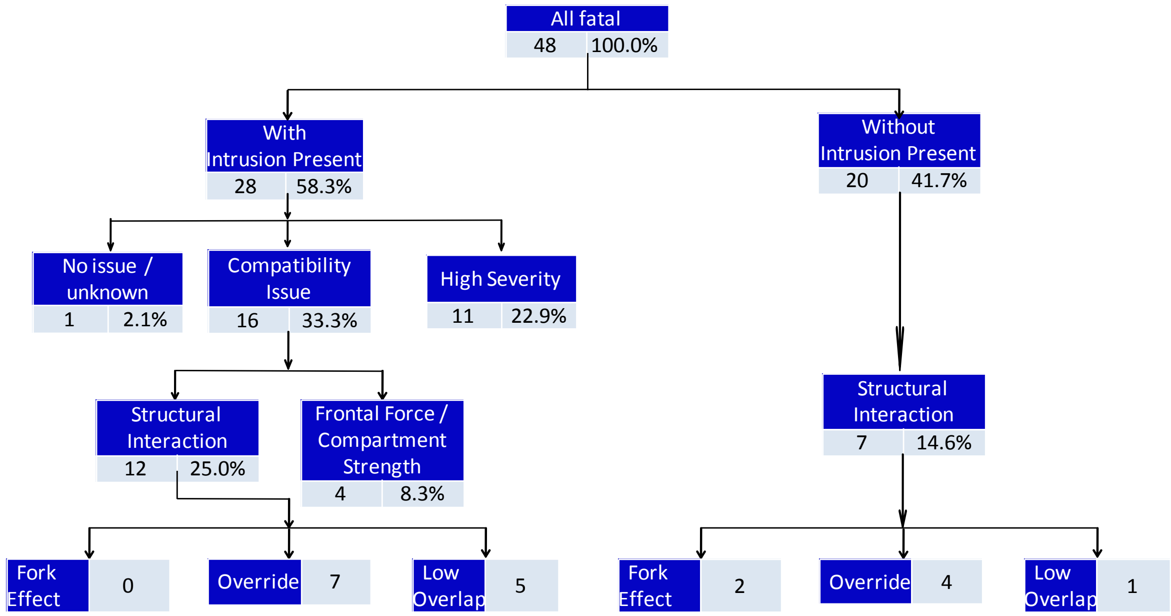


Figure 5.33: Identification of compatibility issues for all fatal cases.

The analysis was subsequently focused on only car-to-car impacts, of which there were 23 fatally injured occupants in 22 vehicles in the dataset (Figure 5.34).

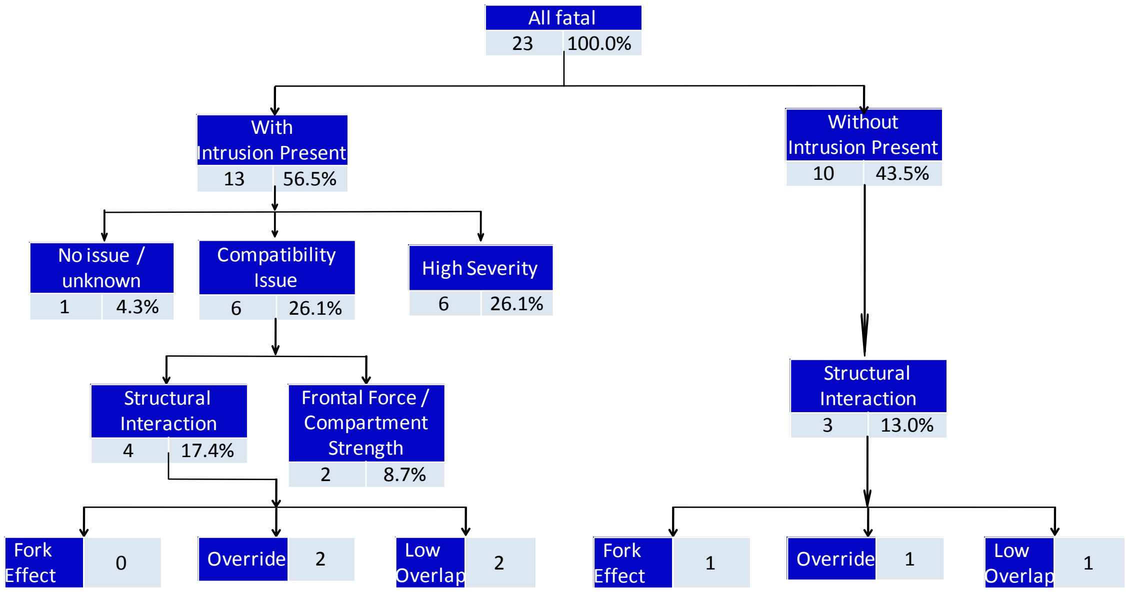


Figure 5.34: Identification of compatibility issues for car-to-car fatal cases.

Intrusion was present for 13 occupants (56%) in 13 vehicles. Structural interaction problems were identified in 7 cases (30%) although it is only in 4 of these cases where there was intrusion (17%) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. Two of these cases were over/underride and 2 were low overlap. Frontal force / compartment strength problems were identified in 2 cases (9%). There was also a high proportion of high severity cases (6 cases 26%) for which the vehicle's deformation was so great that it masked any compatibility issue that may have been present.

An analysis was also performed for car-to-object impacts but there were only 10 occupants in these accidents (Figure 5.35).

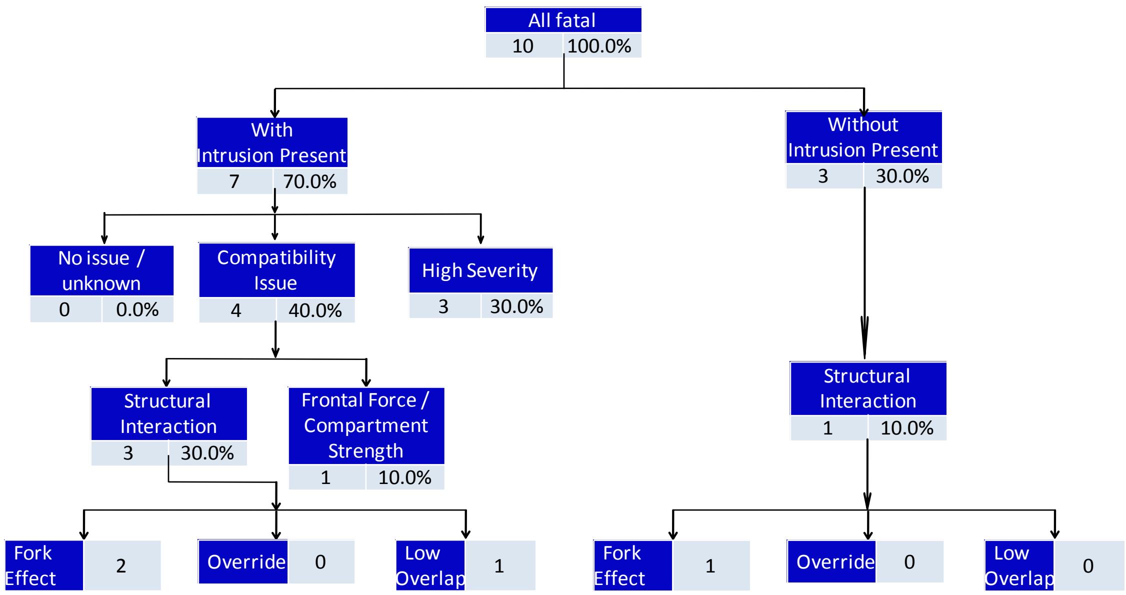


Figure 5.35: Identification of compatibility issues for car-to-object fatal cases.

5.4.3.1 Case Study Examples

This section provides a few examples of case studies in which compatibility issues were identified.

SUV overriding car

In this case a frontal crash between a small car and an SUV resulted in the overriding of the smaller car and subsequent compartment collapse. The mass ratio of the crash from the perspective of the smaller car was approximately 1.9. The driver of the smaller car sustained MAIS 5 thorax injuries as well as multiple AIS 2+ injuries to other body regions, whilst the driver of the SUV sustained MAIS 2 leg injuries. The details and photographs of the vehicles involved are shown in Figure 34.

V1 – Vauxhall Corsa (2002)	**V2 – Mitsubishi Shogun (2003)**
	
980kg kerb mass 55% overlap 46km/h ETS 27cm Facia intrusion 11cm Footwell intrusion Driver (Male, 49) MAIS 5 Thorax [+multiple AIS 3/4]	2000kg kerb mass 48% overlap 33km/h ETS 3cm Facia intrusion 12cm Footwell intrusion Driver (Male, 29) MAIS 2 Legs

Figure 5.36: SUV overriding car (Vauxhall Corsa vs. Mitsubishi Shogun).

Poor structural interaction (Over/underride) between cars of same make and model

In this case two cars of the same make and model were involved in a frontal crash where both vehicles impacted on the nearside of the front structure (not the driver's side in the UK). Despite these vehicles being of the same make and model, and therefore having identical frontal structures, there was a significant difference in the deformation of both the frontal structures and the occupant compartment. The deformation of the vehicles indicated that one car (V1) had overridden the opposing car (V2). This has resulted in significantly more intrusion in the overridden car, and subsequently a worse injury outcome for the driver in this car, despite being seated on the opposite side of the car to the highest levels of intrusion. This case clearly indicated that poor structural interaction is possible between identical cars that are both compliant with R94. The case details are shown in Figure 35.

V1 – Ford Mondeo (2002)	**V2 – Ford Mondeo (2001)**
	
1423kg kerb mass 51% overlap 26km/h ETS 19cm Facia intrusion (near/side) 17cm Footwell intrusion (n/s) No intrusion on off/side Driver (Male, 32) MAIS 2 Shoulder	1384kg kerb mass 50% overlap 46km/h ETS 90cm Facia intrusion (n/s) 118cm Footwell intrusion (n/s) 18cm Facia intrusion (o/s) 5cm Footwell intrusion (o/s) Driver (Male, 53) MAIS 5 Chest

Figure 5.37: Over/underride Ford Mondeo v Ford Mondeo.

Frontal force mismatch between large and small car

This case was a frontal impact between a small car and a large car with an overlap of approximately 60-70 percent. This impact resulted in the overcrushing of the smaller car and subsequent compartment collapse, whilst the larger car had no recorded intrusion. The driver of the smaller car sustained MAIS 5 injury to the thorax, as well as AIS 4 head injury, whilst the driver of the larger car only sustained MAIS 1 injury to the thorax. The case details are shown in Figure 36.

V1 – Peugeot 206	**V2 – Mercedes S320**

	
910kg kerb mass 67% overlap 59km/h ETS 29cm Upper Facia intrusion (o/s) 19cm Knee contact intrusion (o/s) Driver (Female, 68) MAIS 5 Thorax & AIS 4 Head	1925kg kerb mass 57% overlap 28km/h ETS No intrusion Driver (Female, 40) MAIS 1 Thorax

Figure 5.38: Frontal force / compartment strength mismatch Peugeot 206 vs. Mercedes S320.

5.4.4 Results: MAIS 2+ Survived Case Analysis

A detailed case analysis of the CCIS accidents was conducted for the cases were a MAIS 2+ injury was recorded but excluding the fatal accidents reported in the previous section. The results are presented in terms of all cases, car-to-car impact cases and car-to-object impact cases. In total accidents with 100 MAIS 2+ injured occupants in R94 compliant vehicles were analysed.

The results of the MAIS 2+ survived analysis are presented in the figures below. The first, Figure 5.39, gives the combined results of car-to-car and car-to-object collisions. Intrusion was present in 31 of the 100 cases where occupants had MAIS 2+ injuries.

Structural interaction problems were identified in 36 cases (36%) although it is only in 12 of these cases where there was intrusion (12%) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. Three of these cases were fork effect, 4 were over/underride and 5 were low overlap. Frontal force / compartment strength problems were identified in 2 cases (2%).

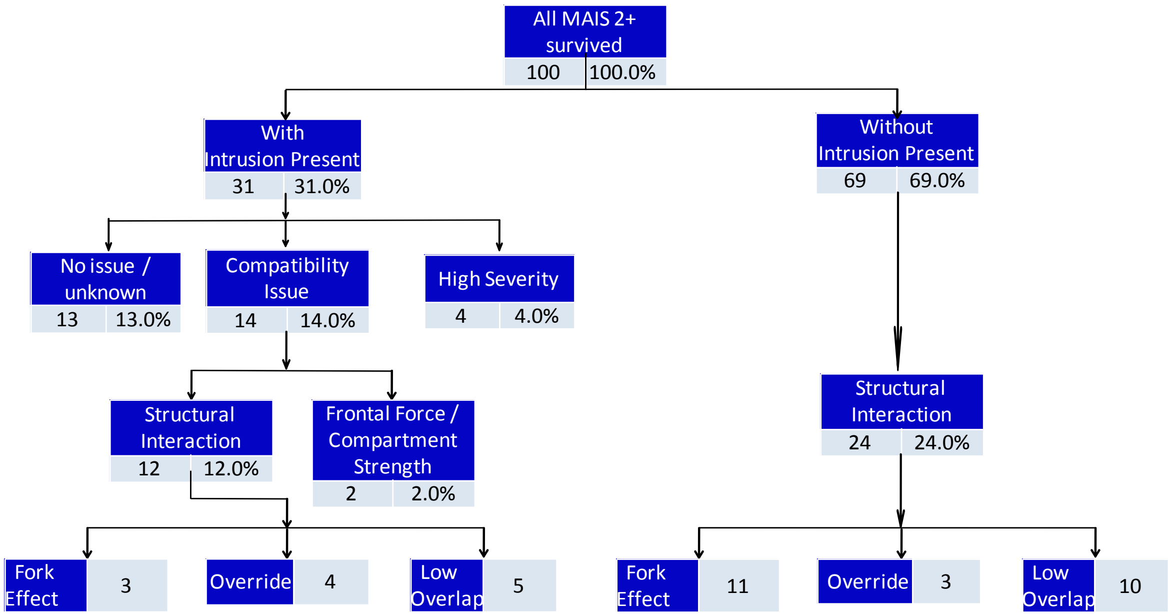


Figure 5.39: Identification of compatibility issues for all MAIS 2+ survived crashes.

A breakdown for the 39 MAIS 2+ survived occupants in car-to-car accidents is shown in Figure 5.40. As for all impacts discussed earlier, a significant portion of the car-to-car crashes involve intrusion and in about half of them compatibility issues were found. Structural interaction issues were identified in 15 cases (38%) although it is only in 9 of these cases there was intrusion (23%).

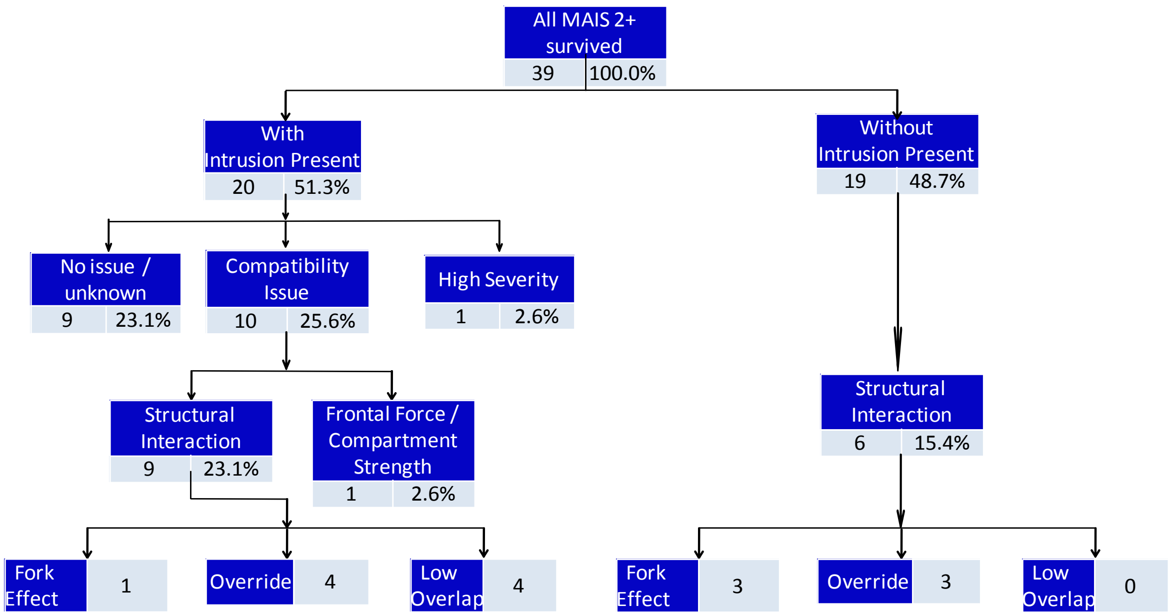


Figure 5.40: Identification of compatibility issues for MAIS 2+ survived car-to-car crashes.

Override was the largest structural interaction issue when intrusion/non-intrusion cases are combined. In four cases there was static geometry information for the vehicles. One case involved 2 identical cars so nominally the static alignment should be exact. The remaining 3 cases had nominal vertical overlaps of less than 50 mm (measured at the crash cans).

The final main category of MAIS 2+ cases to consider was the case when the car hits fixed objects. Both wide and narrow objects crashes are summarised in Figure 5.41 where injuries with and without intrusion are identified. These were the majority of the cases reported earlier in Figure 5.39.

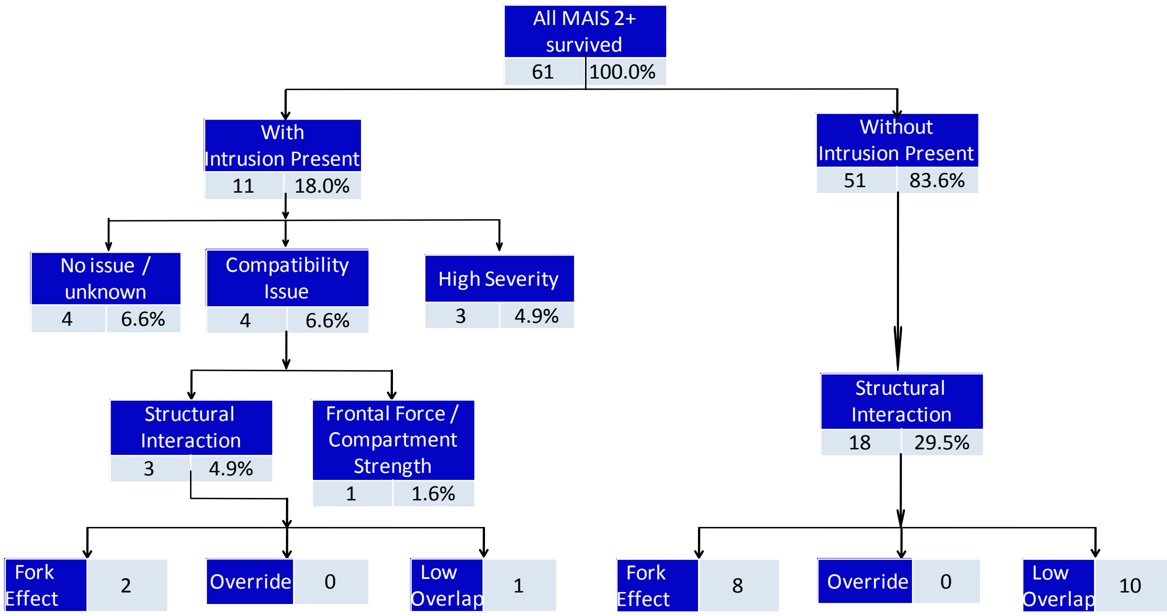


Figure 5.41: Identification of compatibility issues for MAIS 2+ survived car-to-object crashes.

Overall, when intrusion is present about half the cases have compatibility issues, the majority of which are structural interaction. Structural interaction issues were identified in 21 cases (34%) although it is only in 3 of these cases there was intrusion (5%). A large proportion of structural interaction issues related to fork effect are seen for car-to-object impacts. Many of these were related to impacts with narrow objects hitting between the longitudinals.

5.4.4.1 Case Studies Examples

This section provides a few examples of case studies in which compatibility issues were identified for MAIS 2+ survived occupants.

V1 - 2005 Ford Fiesta	V2 - 2006 Mazda 3
	
1105 kg kerb mass 100% overlap, CDC 12:00 50 km/h ETS No intrusions (0)	1265 kg kerb mass 67% overlap, **CDC 01:00** 47 km/h ETS 14 cm Facia intrusion (o/s) 10 cm Knee intrusion (o/s) 9 cm Footwell intrusion (o/s) Driver (Male, 47) MAIS 2, Contact with intrusion

Figure 5.42: Over/underriding Mazda 3 overrides Ford Fiesta.

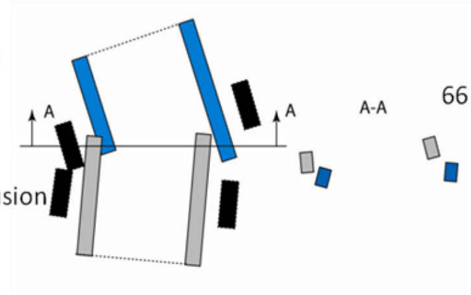
V1 Renault Clio 2004	V2 Fiat Punto 2007
	
945 kg kerb mass 56% overlap, CDC 12:00 45 km/h ETS 2 cm Facia intrusion (n/s) 1 cm Knee intrusion (n/s) 3 cm Footwell intrusion (n/s) Driver (Female, 41) MAIS 2, Contact with no intrusion	1025 kg kerb mass 57% overlap, CDC 12:00 33 km/h ETS No intrusion (0)

Figure 5.43: Fork-effect, intrusion less than 10 cm. Renault Clio vs Fiat Punto.

V1 – Mazda 6, 2007

V2 – Audi A3, 2005

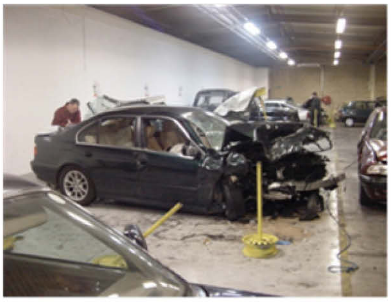
1310 kg kerb mass
48 % overlap, CDC 11:00
39 km/h ETS
No intrusions
Driver (Male, 43)
MAIS2, Contact with no intrusion



kg kerb mass
66 % overlap, CDC 12:00
41 km/h ETS
No intrusions

Figure 5.44: Over/underriding with fork effect (classified as overriding because this judged more severe) Mazda 6 vs Audi A3.

V1 – BMW 525 2003



1560 kg kerb mass
60% overlap, CDC 12:00
40 km/h ETS
9 cm Facia intrusion (o/s)
12 cm Knee intrusion (o/s)
22 cm Footwell intrusion (o/s)
Driver (Male, 72)
MAIS2, Restraint

V2 – Fiat punto 2001

975 kg kerb mass
50% overlap, CDC 12:00
41 km/h ETS
36 cm Facia intrusion (o/s)
36 cm Knee intrusion (o/s)
26 cm Footwell intrusion (o/s)
Driver (Male, 57)
MAIS5, restraint and other

Figure 5.45: Frontal force / compartment strength (BMW 525 vs Fiat Punto), much greater intrusion in Punto.

V1 – Vauxall Vectra 2003

1450 kg kerb mass
34% overlap, CDC 12:00
27 km/h ETS
2 cm Facia intrusion (o/s)
5 cm Knee intrusion (o/s)
0 cm Footwell intrusion (o/s)
Driver (Female, 49)
MAIS2, restraint

V2 – Ford Fiesta 2006

1143 kg kerb mass
34% overlap, CDC 12:00
38 km/h ETS
2 cm Facia intrusion (o/s)
12 cm Knee intrusion (o/s)
6 cm Footwell intrusion (o/s)
Driver (Male, 66)
MAIS1

Figure 5.46: Frontal force / compartment strength (Vectra vs Fiesta), much greater intrusion in Fiesta.

5.4.5 Conclusions CCIS Detailed Case Analysis

- Poor structural interaction has been observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.
  - Structural interaction problems identified in 40% of fatal and 36% of MAIS 2+ injured cases. However, only in 25% of fatal and 12% of MAIS 2+ cases there was intrusion present and thus it can be said definitely that improved structural interaction would have improved the safety performance of the car[4].
- Frontal force and/or compartment strength mismatch issues between cars in the current fleet appear[5] to be less of an issue than poor structural interaction.
  - For all accidents, force and/or compartment strength mismatch problems identified for 8% of fatal and 2% MAIS 2+ survived occupants. However, it should be noted that force and/or compartment strength mismatch problems can only be identified for accidents in which there is compartment intrusion into the vehicle.
  - For car-to-car impacts force and/or compartment strength mismatch problems identified for 9% of fatal and 3% MAIS 2+ survived occupants

[4] It should be noted that in 23% of the fatal cases the accident severity was so high that it was not possible to determine whether or not a compatibility issue had occurred.
[5] Note: structural interaction problems could be masking frontal force mismatch problems

6 GERMAN ACCIDENT ANALYSIS

6.1 Data Selection

6.1.1 Approach

The German data sample analysed in FIMCAR included all significant frontal collisions with passenger cars involved that were recorded and reconstructed within GIDAS until the end of year 2009. Statistical analyses were conducted using the statistical analysis software R (version 2.10.1). To consider vehicle compliance with Regulation 94, only passenger cars were included with the first registration in year 2000 or later. In GIDAS, this date is recorded for each vehicle involved with the help of its official vehicle registration certificate. No further check for the R94 compliance has been done. Furthermore, the accident analyses focused on the injuries of drivers and front seat passengers with a minimum age of 12 years; hence all rear seat occupants are excluded. Accidents of all injury severities were regarded whereby vehicles sustained damage mainly at the front (zone 1 of VDI2, see Glossary) and the principal direction of force came of 11, 12 or 1 o'clock (VDI1, see Glossary). To avoid false conclusions, multiple collisions and rollover accidents were excluded consequently from this analysis.

The initial high level analysis (Section 6.2) provides general information and distributions on OCCUPANT and VEHICLE level with regard to gender, injury severity, seating position, age and collision partner groups. Following this, detailed analysis of injuries (Section 6.3) is provided. The collision events are further analysed in Section 6.4 in terms of speed, intrusions, overlap, vehicle mass dependencies, injury mechanisms and acceleration loading. Finally, section 6.5 contains conclusions related to the identified compatibility issues, the nature of injuries and determined significant injury mechanisms. The GIDAS variables VDI 1, 2 and 3 (vehicle deformation indices, see 6.1.3) are used to conduct this analysis and are introduced within the appropriated sections.

6.1.2 Initial GIDAS Dataset

The GIDAS dataset contained all significant frontal collisions with passenger cars with dates of their first registration younger than year 2000. Please see Section 6.1.1 for the entire data query. Two main datasets could be provided. The first one regarded the OCCUPANT LEVEL information and included all involved people (n = 2604). The second one focused on the VEHICLE LEVEL and comprised each vehicle involved in the crashes.

Four main groups were created to separate the results into crashes related to their collision partners and are shown in Table 7.

Table 7: Groups of collision partners.

Abbreviation	Description
CAR_CAR	Passenger car vs. passenger car All vehicles with a car body.
CAR_HGV	Passenger car vs. heavy good vehicle Included are trucks and buses.
CAR_OBJ	Passenger car vs. object Non-vehicles, in particular roadside elements such as trees and pillars.
CAR_OTH	Passenger car vs. other All remaining vehicles, in particular bicycles and powered two-wheelers.

The OCCUPANT LEVEL information of all crashes in the initial dataset is shown in Table 8 whereby absolute numbers and percentages are given. The injured occupants were subdivided into slightly injured people with MAIS 1 and seriously injured people (MAIS 2+) including fatalities. Furthermore, uninjured people (MAIS 0) and people with unknown degree of injury severity (MAIS 9) were reported. This whole dataset (n=2,604) contained 16 fatalities which likely can be assigned to the group of seriously injured people and were extracted separately per collision partner group. In total, 2,604 occupants are considered with quite different injury severity distributions within the collision partner groups.

Table 8: Initial dataset GIDAS analysis (distribution into injury severity)

	Serious (MAIS 2+)		Slight (MAIS 1)	Uninjured (MAIS 0)	Unknown (MAIS 9)	Total		Fatalities
	n	%	n	n	n	n	%	n
CAR_CAR	92	54	499	724	25	1340	51	6
CAR_HGV	20	12	49	21	13	103	4	3
CAR_OBJ	57	33	142	276	14	489	19	7
CAR_OTH	2	1	11	657	2	672	26	0
Total	171	100	701	1678	54	2604	100	16

6.1.3 Explanation of GIDAS Variable Vehicle Deformation Index

The variable Vehicle Deformation Index (VDI) was used for most of the analysis of the accidents in the GIDAS sample. The VDI is similar to the Collision Deformation Characteristics (CDC). The VDI describes in 7 parts (VDI1 – VDI7) the principle direction of force, the general location of the deformation, the horizontal and vertical distribution of the deformation, a brief description of the contact and the degree of deformation. Within this report VDI1, VDI2 and VDI3 were used. The VDI is similar to the Collision Deformation Characteristics (CDC). The VDI describes in 7 parts (VDI1 – VDI7) the principle direction of force, the general location of the deformation, the horizontal and vertical distribution of the deformation, a brief description of the contact and the degree of deformation. Within this report VDI1, VDI2 and VDI3 were used.

VDI1 describes the Principle Direction of Force (PDOF) using a clock direction. Within the GIDAS sample PDOF is normally calculated, in other data sets it is mostly estimated. VDI1 directions 11, 12 and 1 were considered to be frontal impact accidents these correspond to an angle of -45° to +45°.

VDI2 describes which part of the car is deformed. For this study only accidents with the vehicle front being deformed were included.

VDI3 describes the horizontal distribution of the deformation. Figure 6.1 shows the classification used for frontal impacts.

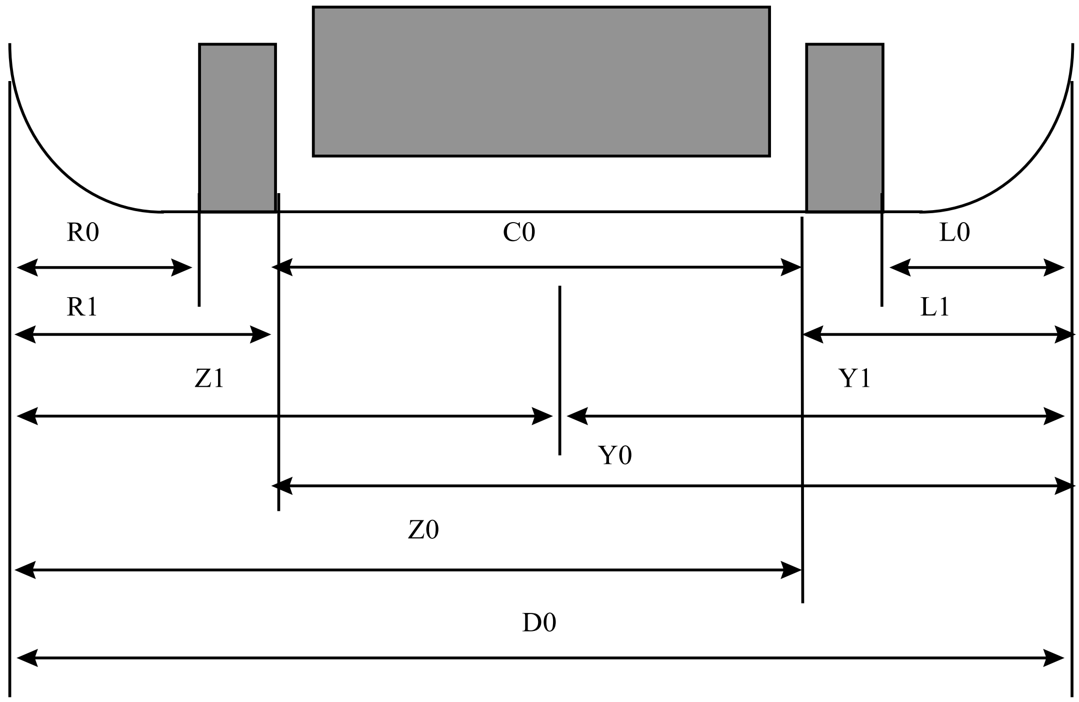


Figure 6.1: VDI3 classification for frontal impact accidents.

6.2 General Overview GIDAS Sample

This section gives some sample checks that have been done in order to provide a general overview of the generated dataset. The overall MAIS distribution of all involved people in the crashes is shown in Figure 6.2. Subdivided into the collision partner groups, most frequent events could be identified in car-to-car crashes followed by car crashes against objects and others.

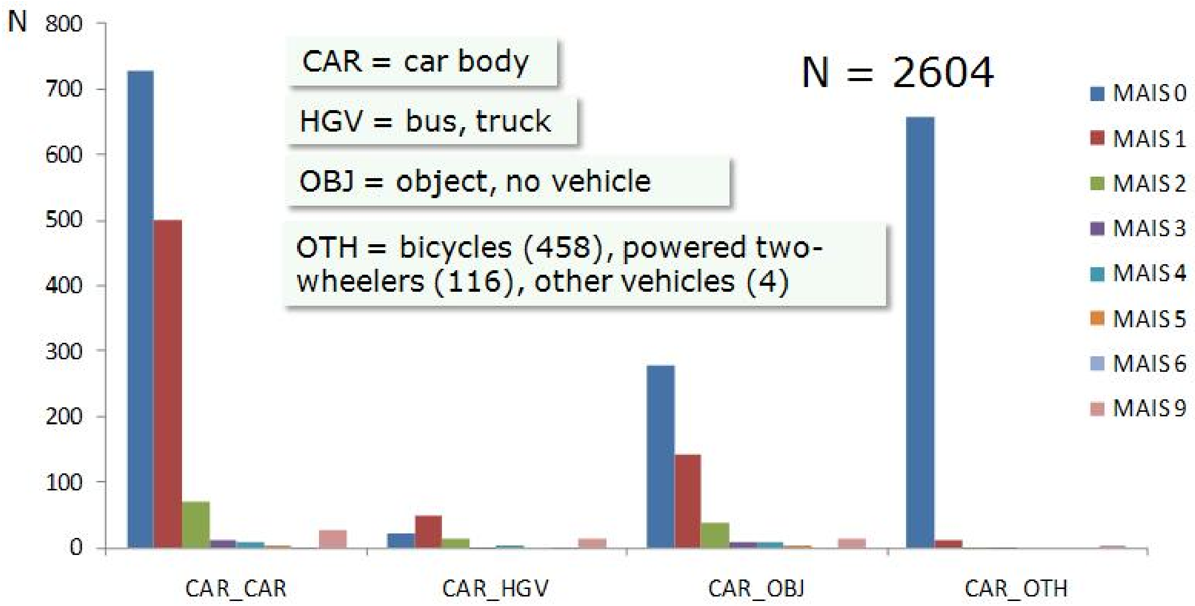


Figure 6.2: MAIS distribution on OCCUPANT LEVEL.

The absolute occupant numbers primarily show the huge amount of relevant crashes between two passenger cars. Involved people were mostly uninjured or suffered injuries of MAIS 1 or 2. The information in Figure 6.2 implies a higher injury severity risk in crashes of cars against heavy good vehicles and objects than for the other groups. Almost no injuries occurred to passenger car occupants whilst hitting “other” collision objects.

Figure 6.3 shows the occupant age distribution subdivided into the four collision partner groups. Again, the total number of involved people was 2,604 (OCCUPANT LEVEL) and the assigned age ranges show different distributions for the different collision partners. No further analysis was done for the national representativeness of these figures to driver and front seat passenger age distributions in Germany. The total age group distribution reflects the high accident number of crashes between two cars. Compared to other collision types, there were large differences in the age distribution identified in crashes against objects for which younger people were more frequently involved.

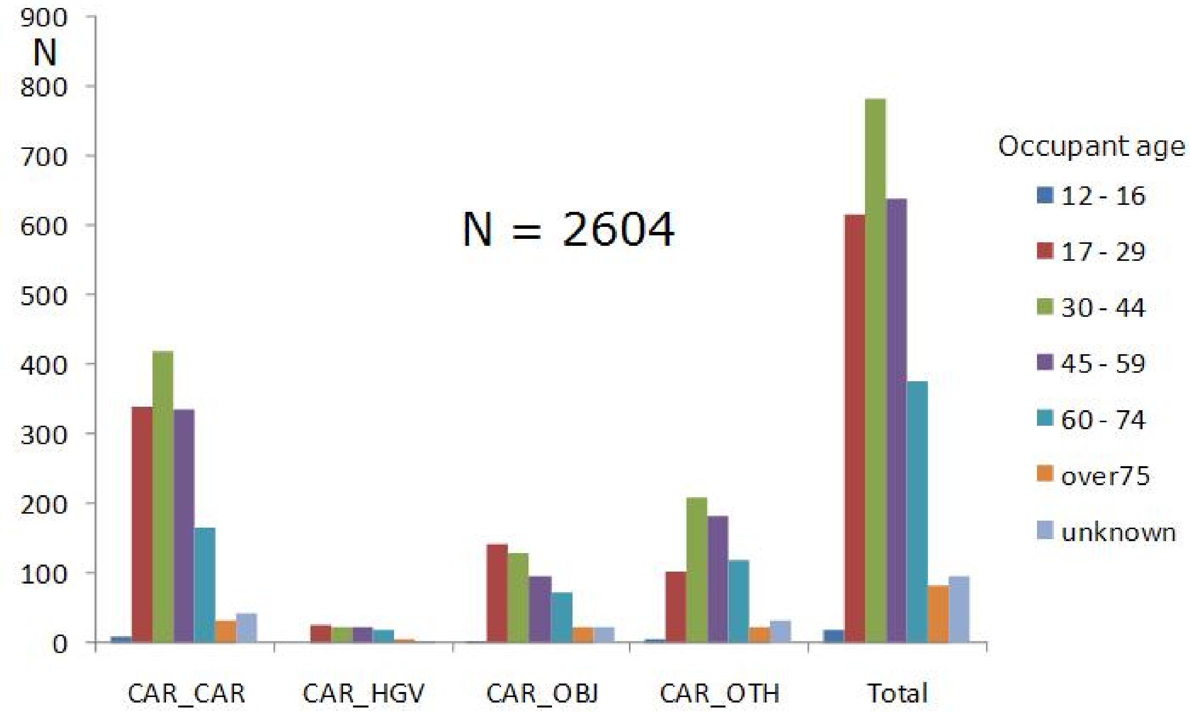


Figure 6.3: Occupant age distribution.

Looking at the gender on OCCUPANT LEVEL of all crashes 38% of the involved people were females. Furthermore, Figure 6.4 demonstrates nearly the same distribution rate within each collision partner groups (38% of female in CAR_CAR, 37% of female in CAR_OBJ).

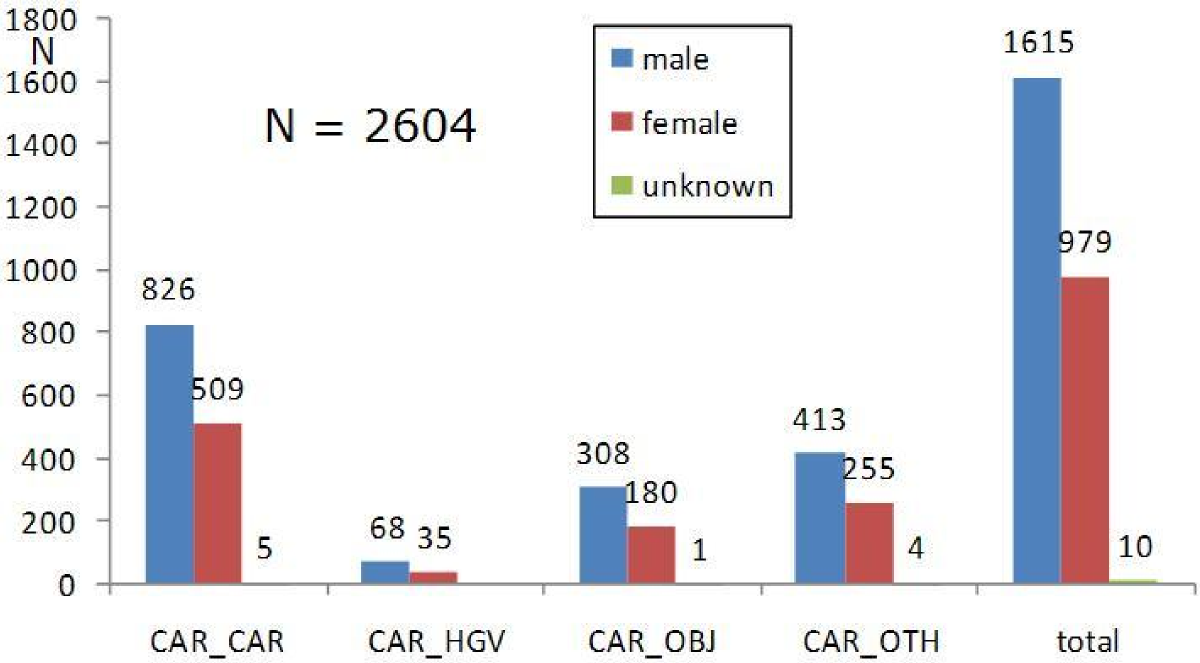


Figure 6.4: Gender distribution of crash involved people.

With a focus on the ratio of occupant's gender and the MAIS, Figure 6.5 shows the distribution of males and females related to their seating position. To ensure the quality and correctness of statements the sample was restricted to people whose seatbelt usage was positively assigned.

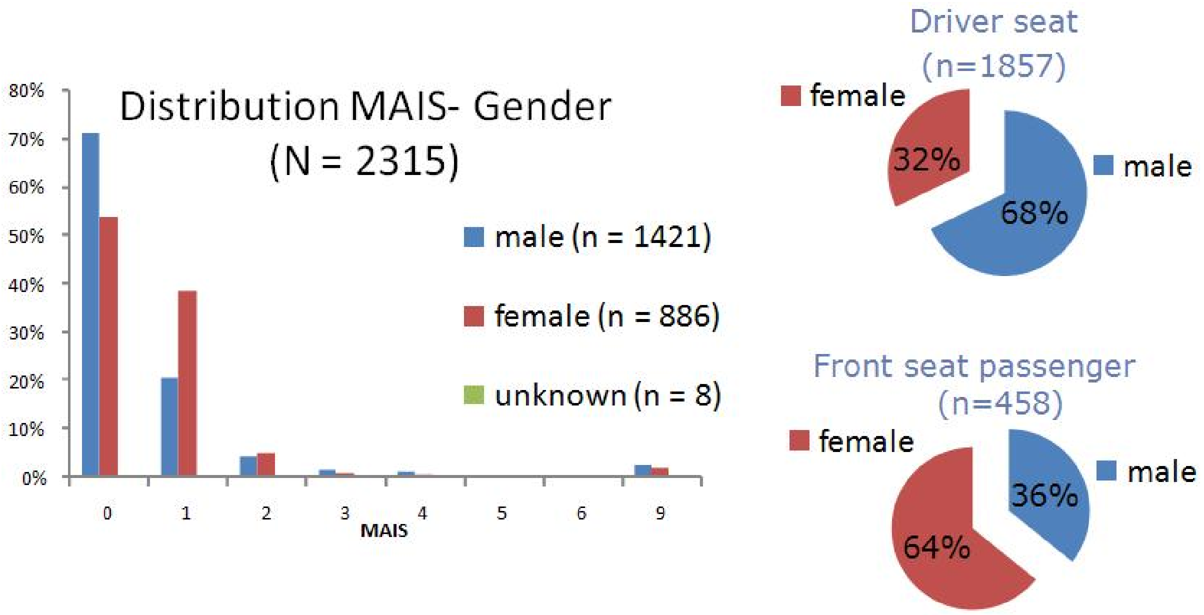


Figure 6.5: MAIS – gender distribution of belted occupants.

The MAIS – gender distribution classifies all men and women (each gender 100%), with their overall MAIS. Male occupants seemed to be more frequently uninjured (MAIS 0) than female ones. Most MAIS 1 and MAIS 2 injuries could be assigned to women whilst male occupants sustained slightly more frequent injuries of MAIS 3 or MAIS 4. To bring these facts into relation to the likely contributing seating position, two diagrams were added on the right side of the figure. Regarding the seats, approximately two-thirds of all drivers were male and again approximately two-thirds of the front seat passengers were female. Additionally, the total numbers of the occupied driver seats (n=1,857) and the front seats (n=458) indicated that about 1,400 occupants travelled alone or with rear seat occupants. Further studies, such as matched-pair-analysis, could show relations between these seating positions, frequencies of use by gender and the related injury severity but were omitted here.

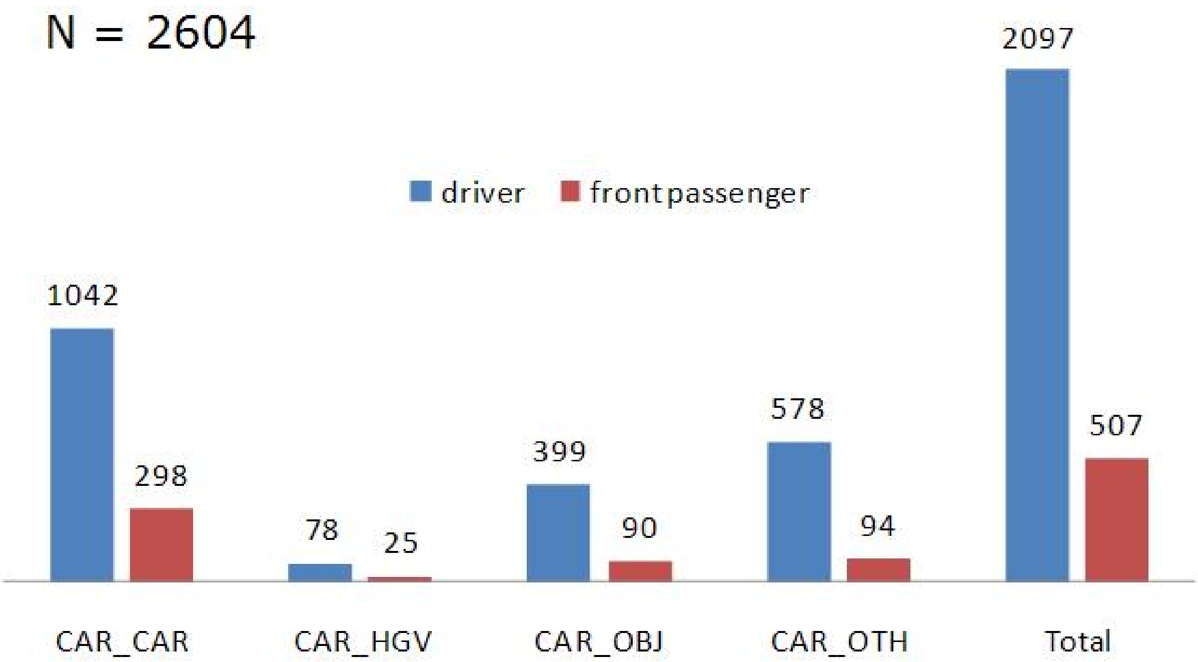


Figure 6.6: Distribution of drivers and front seat passengers in collision partner groups.

To give a generalised view on the distribution of the occupied seat, Figure 6.6 comprises all people in the dataset and shows the total numbers subdivided into the collision partner groups.

In total, nearly 20% of people were front seat passengers. In the group CAR_CAR 22% of the involved people could be assigned to be front passengers, 18% in the group CAR_OBJ and 14% in the group CAR_OTH. The ratio of drivers and front seat passengers in the group CAR_HGV (24%) might be a result of the low number of accidents in this group and could be misleading.

The pie diagram in Figure 6.7 shows the principal directions of forces (PDOF, called VDI1 in the diagram) among the initially determined directions 11, 12 or 1 o'clock. Half of all crashes occurred in frontal longitudinal direction and nearly a quarter of all crashes were assigned to the frontal left as well as to the frontal right direction.

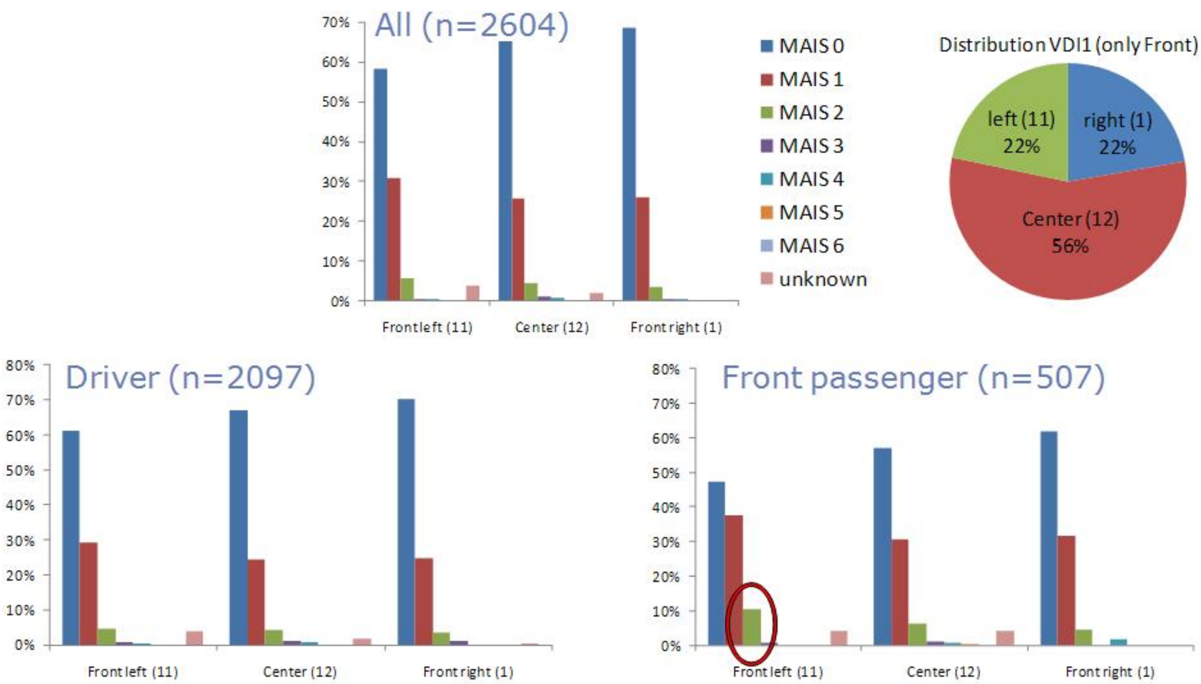


Figure 6.7: MAIS – VDI1 (principal direction of force).

The bar charts in Figure 6.7 point out the MAIS values of all considered occupants related to the principal direction of forces whereby each direction is 100% in itself. The overall view shows more seriously injured persons with the PDOF coming from front left than from centre or front right. In general, drivers and front seat passengers suffered similarly from the direction of force but there was also a small tendency to sustain more severe injuries as a front passenger compared to drivers when comparing the MAIS 0 - 2 bars. In particular, the red circled MAIS 2 bar of front passengers indicates a higher injury severity for forces coming from front left than from other directions or the driver position that might be caused by slipping out of the seatbelt. To explain this trend closer, injury mechanisms would have to be identified through further investigation at the individual injury level that could not be done within this analysis.

6.3 Injury Analysis

The share of all occupants within the collision partner groups is shown as percentages in Figure 6.8 (each group is 100%). Slight and severe injuries were very unlikely for car occupants in the group passenger cars against others. Contrarily, the highest probability to get severely injured was in car crashes against heavy good vehicles. When comparing the groups CAR_CAR and CAR_OBJ, more slight injuries (MAIS 1) occurred to occupants in crashes against passenger cars and more severe injuries (MAIS 2 and 3) occurred in crashes with objects.

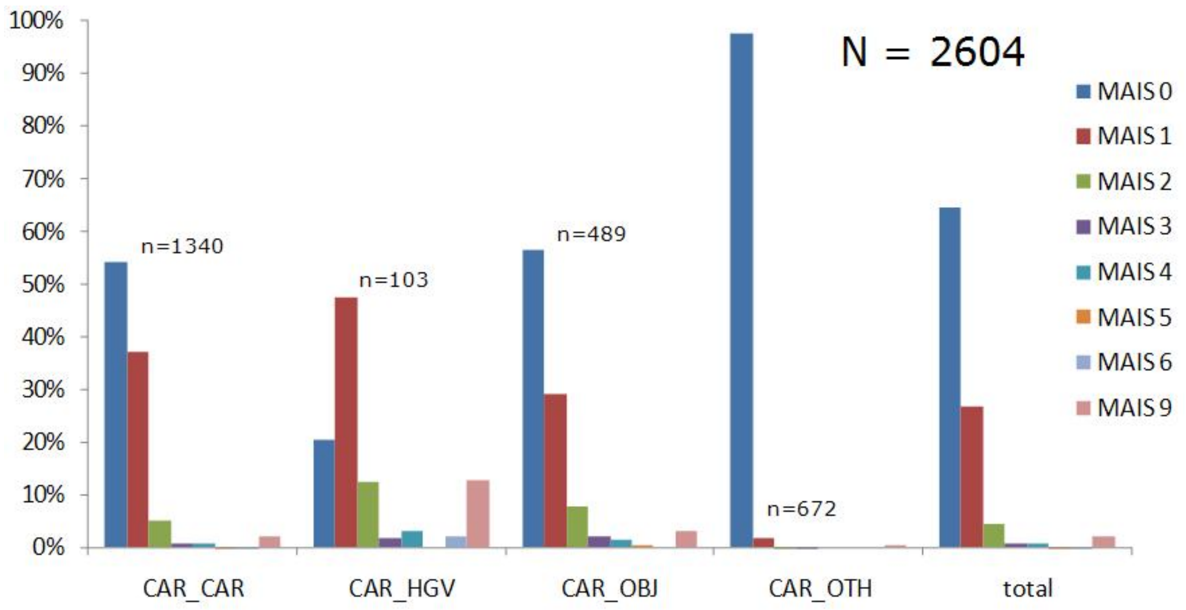


Figure 6.8: MAIS distribution by percentage of all occupants.

To analyse the injury mechanisms in more detail it's necessary to have a look at the body regions concerned. Therefore, the highest AIS values of predetermined regions (head, neck, arms, thorax, abdomen, pelvis and legs) were compiled in Figure 6.9 at the OCCUPANT LEVEL for all collision partner groups. To address the severely injured people, the sample was reduced to belted occupants with a minimum value of MAIS 2 and maximum MAIS 4. People with unknown overall MAIS and fatalities are excluded.

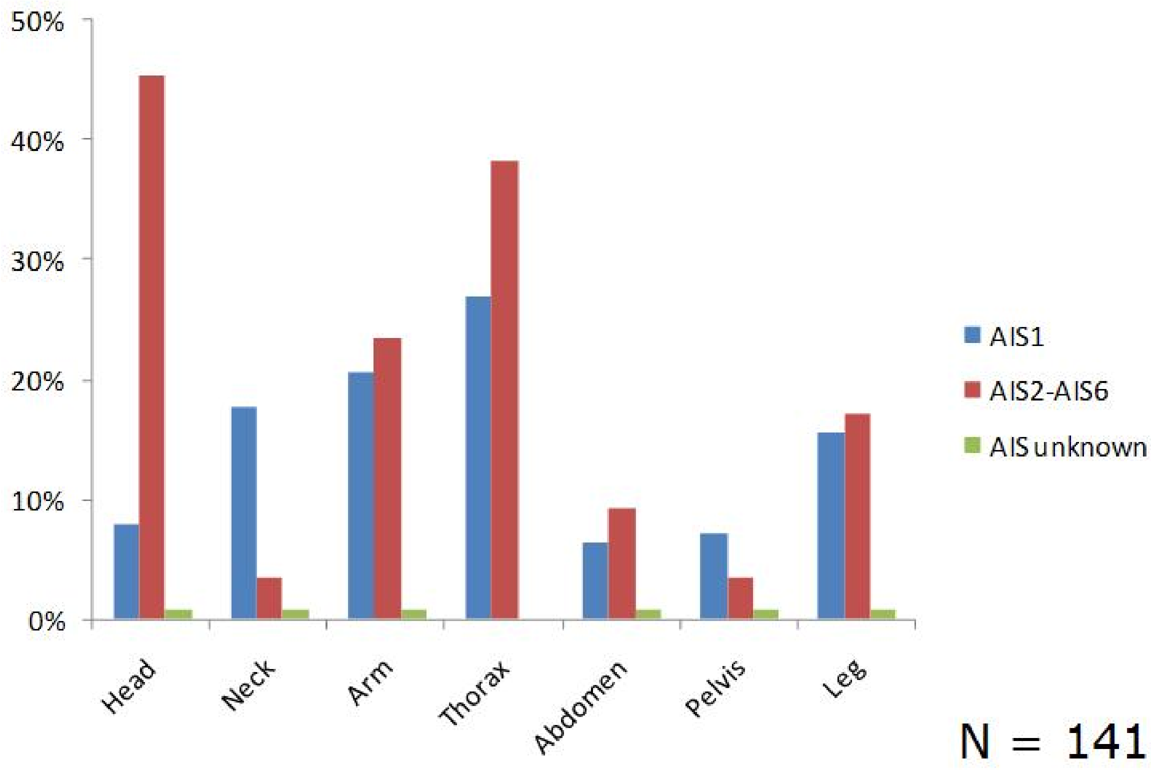


Figure 6.9: AIS distribution by body regions for all groups.

The percentages were derived separately for each body region considering all occupants (100%) in this reduced data sample (n = 141) with MAIS 2+ injured people. The remaining percentages per body region were assigned to AIS 1 or uninjured, respectively. It can be seen that highest injury rates (AIS 2+) were located in the head region, followed by thorax. Regarding AIS 1+ injuries and comparing all body regions thorax injuries could be identified as most frequently (approx. two-thirds of observed people suffered from thorax injuries).

Using the same data query as above but focusing on the collision partner group passenger car against passenger car (car-to-car) Figure 6.10 demonstrates differing distributions compared to Figure 6.9. Again, the body regions thorax and head showed highest injury rates (AIS 2+) compared to all regions but severe head injuries decreased significantly and the thorax is seen to be the most frequent severely injured body region.

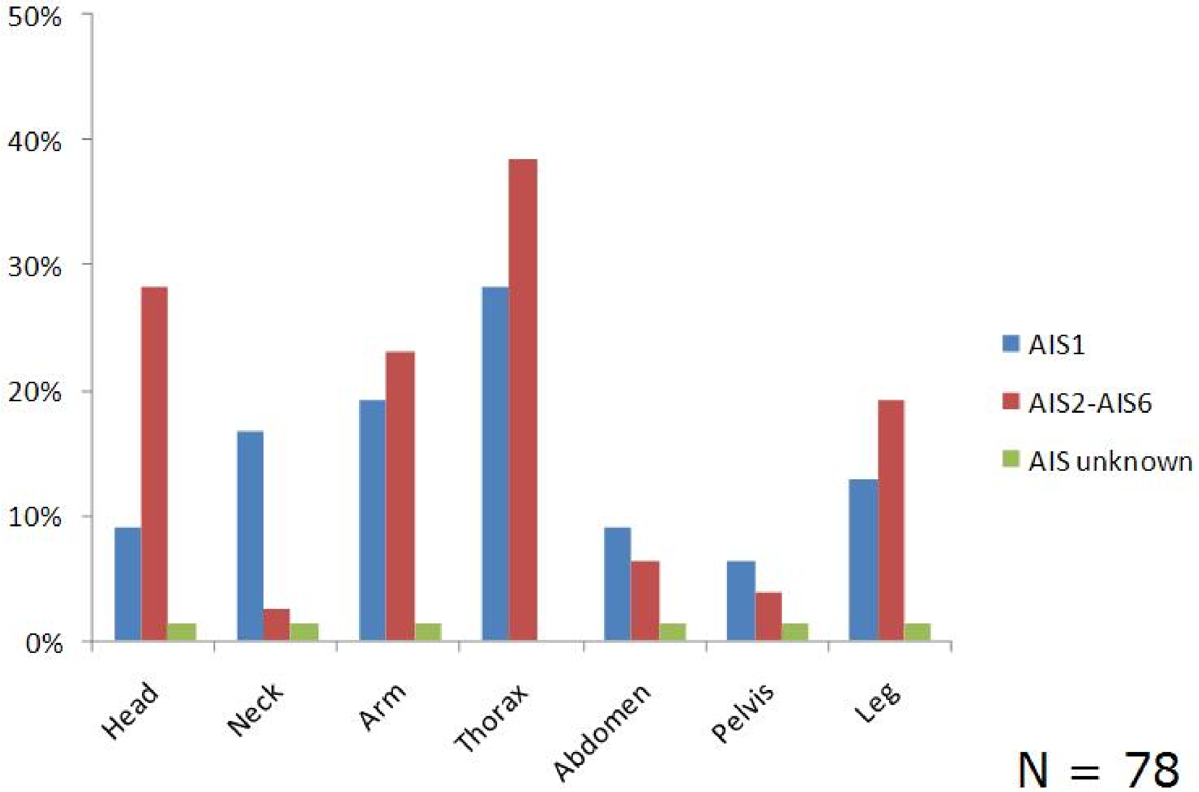


Figure 6.10: AIS distribution by body regions exclusively for group CAR_CAR.

6.4 Collision Analysis

6.4.1 EES

The Energy Equivalent Speed (EES) is a theoretical value that describes the amount of energy a vehicle absorbed in an accident. EES is similar to the collision speed when crashing with large overlap into a rigid obstacle. This value is used in Figure 6.11 to compare the different collision partner groups with each other at the VEHICLE LEVEL (n = 2097). Comparing the sizes of bars per group (each is 100%) showed significant differences between collision severities with the collision partners.

Crashes of passenger cars against others could be classified as a low EES collision (1 - 19 km/h), in contrast to collisions between cars and heavy good vehicles with most frequent values in a range of 10 - 39 km/h in about 75% of the cases. When crashing with an object, approximately one-third of the vehicles had an EES lower than 10 km/h and further one-third was analysed in a range of 10 - 39 km/h. In addition, CAR_OBJ and CAR_OTH were groups with each about 30% of unknown EES values.

When looking at crashes between two cars again approximately 75% of the vehicles had an EES in the range of 10 - 39 km/h and two-thirds of all reviewed crashes showed EES values between 10 - 29 km/h.

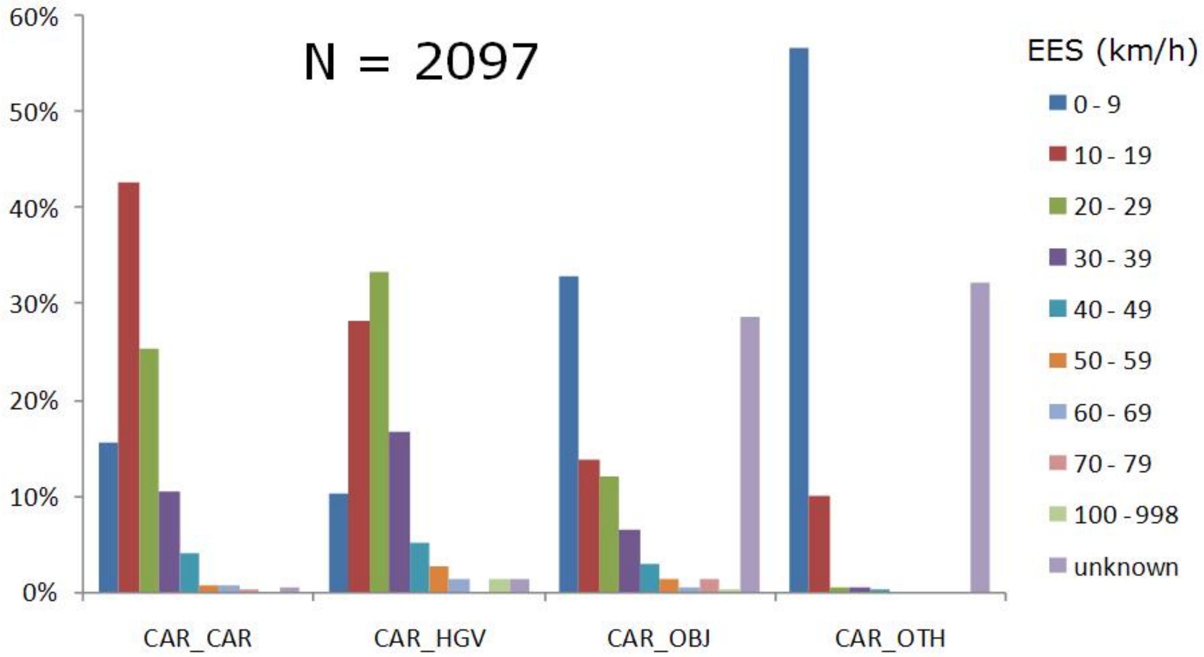


Figure 6.11: EES distribution on VEHICLE LEVEL.

The EES distribution for all vehicles is shown in Table 9 and divided into different EES intervals.

Table 9: EES (km/h) share of all vehicles (n = 2097) in the data set

km/h	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	>100	Unknown
n	629	579	342	151	57	15	9	7	2	306

To address the severely injured people, the sample was reduced to vehicles with belted occupants who survived and suffered from a MAIS 2+ injuries. People with unknown overall MAIS and fatalities had been excluded. Figure 6.12 contains this data at the VEHICLE LEVEL (n = 101) whereby each collision partner group is 100%. Due to the small number of cases within the groups CAR_HGV and CAR_OTH, the focus of this chart is on crashes CAR_CAR, CAR_OBJ and TOTAL. About 70% of all severe frontal crashes in this dataset occurred in an EES range of 10-39 km/h and in general, EES values in all collision partner groups increased compared to Figure 6.11. Approximately 75% of crashes between two passenger cars (red circled area) occurred at EES values of 10 - 39 km/h (red circle in Figure 6.11) and a further 12% in values of 40 - 49 km/h but only 6% of all vehicles showed EES values around the Euro NCAP test severity.

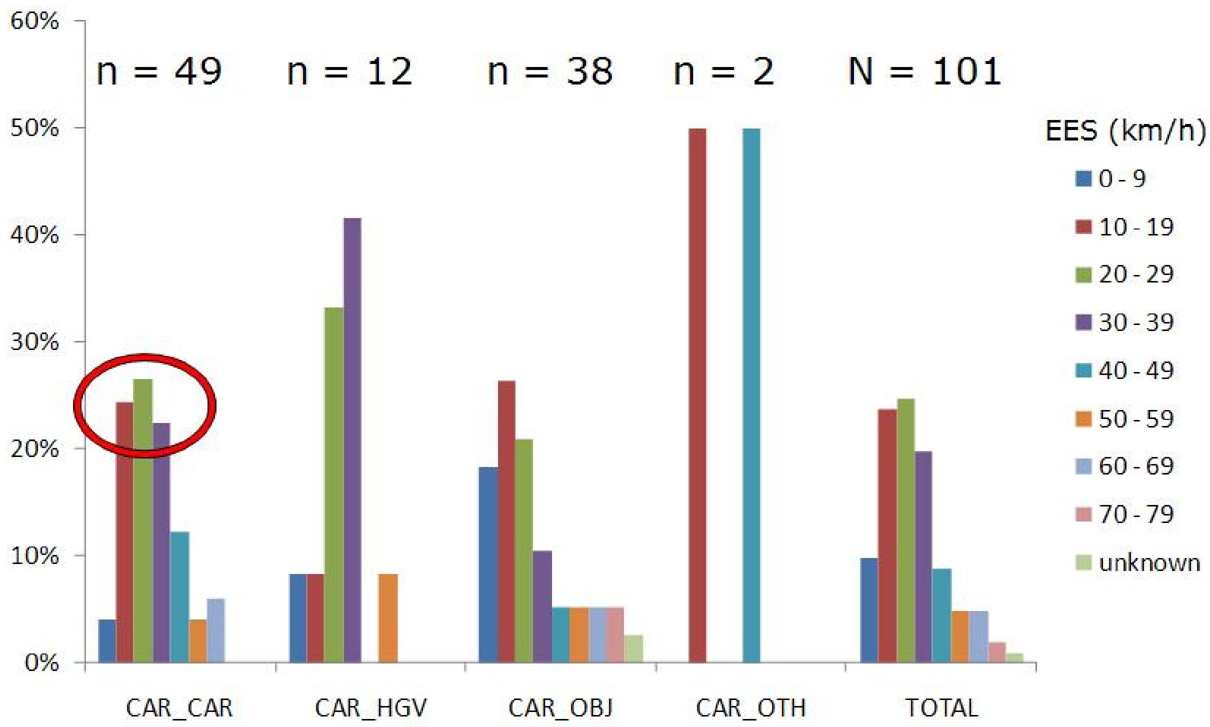


Figure 6.12: EES distribution on severely injured people (MAIS 2+).

6.4.2 Investigation of Intrusions

This section investigates in detail the compartment intrusions to the car. For GIDAS, analysis intrusion is considered to be present if visible loss of stability of relevant parts of the cabin was recognised or a door opening reduction (DOR) of more than 10 cm was recorded.

Table 10 gives an overview about the share of involved vehicles (n = 2,097) classified by the collision partner groups. Nearly half of all vehicles could be listed as frontal crashes between two passenger cars.

Table 10: Numbers of involved vehicles in the entire data set

Number of vehicles	CAR_CAR	CAR_HGV	CAR_OBJ	CAR_OTH
n = 2097	1043	78	398	578

Figure 6.13 compares the observed stability losses of a-pillars and the bulkheads on both left and right sides of the vehicles. For each combination, the crash partner groups were set to 100% to highlight differences. The charts demonstrate the overall rare occurrence of significant deformations. Crashes between passenger cars and heavy good vehicles were the most severe followed by crashes against objects. In less than 2% of all CAR_CAR crashes in this dataset the a-pillars showed stability losses on the left or right side. Furthermore, in CAR_CAR collisions there were a few more cases with stability loss on the left side compared to the right side in contrast to CAR_OBJ collisions where this issue was shifted to the right side.

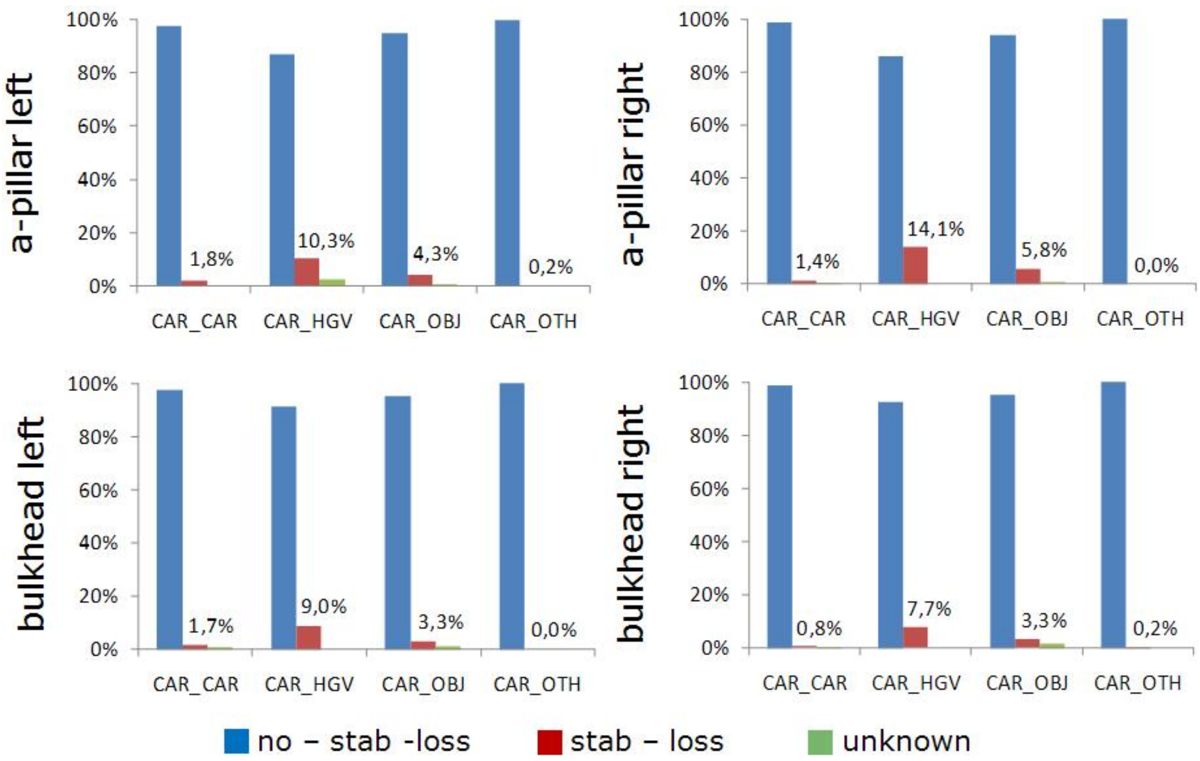


Figure 6.13: Stability losses of pillars and bulkheads for all involved vehicles

Considering further significant occupant compartment parts Figure 6.14 focuses on VEHICLE LEVEL on stability losses of a-pillars, bulkheads and the dashboard on both left and right side of all vehicles (n = 2097).

Crashes between passenger cars and heavy good vehicles led to most severe outcomes to the compartment. Stability losses of the a-pillar of cars occurred in about 12% of all crashes of type CAR_HGV, in about 5% of type CAR_OBJ, in 2% of type CAR_CAR (marked by red circle) and almost never in crashes of type CAR_OTH. All the data presented in Figure 6.13 report the rates a component exhibited instability. Considering that different combinations of instability can occur (a-pillar, bulkhead, DOR) on each side (left and right), one can assume that the occupant compartment was compromised in more cases than indicated by one bar in Figure 6.13. This maximum rate of compartment instability occurred for impacts with HGVs and was relatively rare in car-to-car crashes.

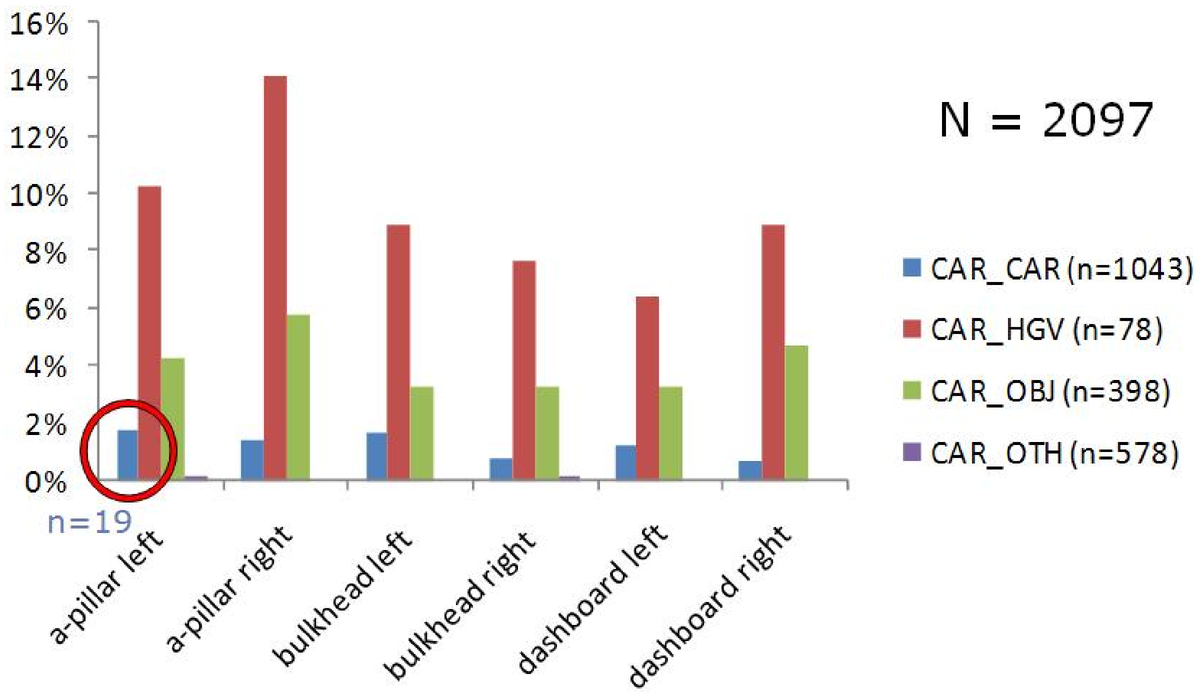


Figure 6.14: Stability losses of significant compartment parts.

Creating a new sample to address the severely injured people was realised by reducing the selection of vehicles to only belted drivers and front passengers who suffered from a MAIS 2+ injury. People with unknown MAIS were excluded. Figure 6.15 contains this data at the VEHICLE LEVEL (n = 105) whereby each collision partner group is 100% per compartment component. Paying attention to the decreasing total numbers leads the focus of this chart to CAR_CAR and CAR_OBJ cases, although crashes of passenger cars against heavy good vehicles led to most severe damages to the compartment. Stability losses of one a-pillar of cars occurred here in about 20% of type CAR_OBJ, in 8% of type CAR_CAR (marked by red circle) and almost never in crashes of type CAR_OTH. Left side compartment parts collapsed more frequently in crashes CAR_CAR than on the right side.

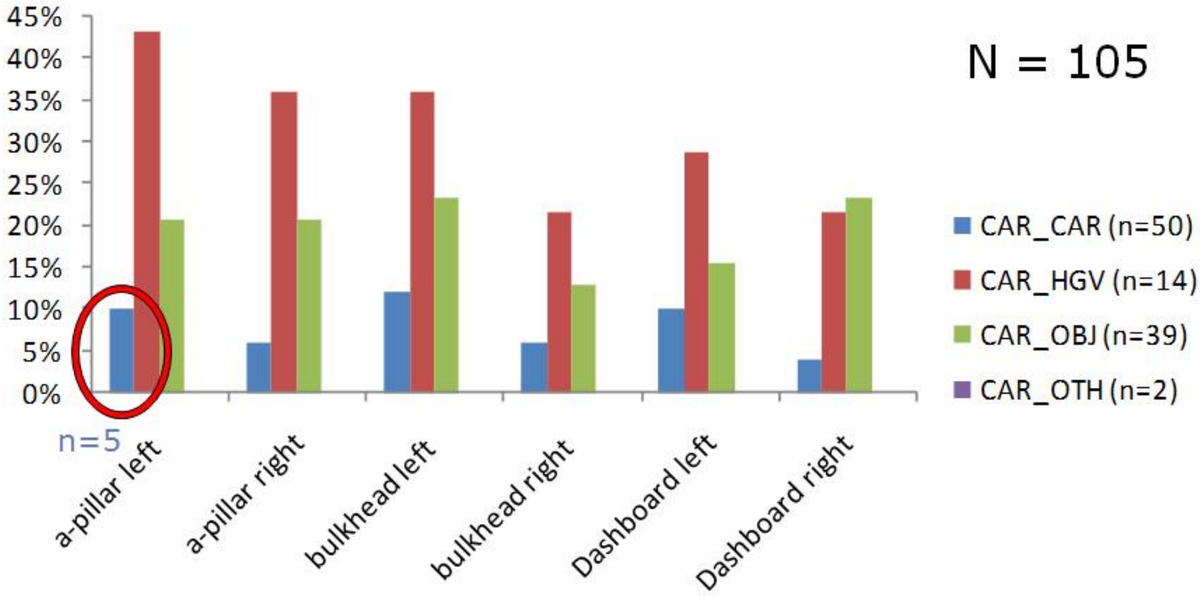


Figure 6.15: Stability losses in crashes involving occupants with MAIS 2+.

The red circled bars in Figure 6.14 and Figure 6.15 show the relatively low proportions of cabin stability losses in crashes between two cars compared to other collision partner groups.

Searching for another value in GIDAS to analyse severe damage to the occupant compartment led to the Door Opening Reduction (DOR) data which is shown in Figure 6.16. The upper bar chart includes the entire data set on VEHICLE LEVEL (n = 2,097) and gives an impression about the dimensions of gathered deformation data at the accident scene. In total, in up to 10% of all involved vehicles door opening reductions could be observed whereby a tendency of more frequently damages to the left side could be noted. Heavy DOR with 10 cm and more occurred in 1 - 2% to the vehicles.

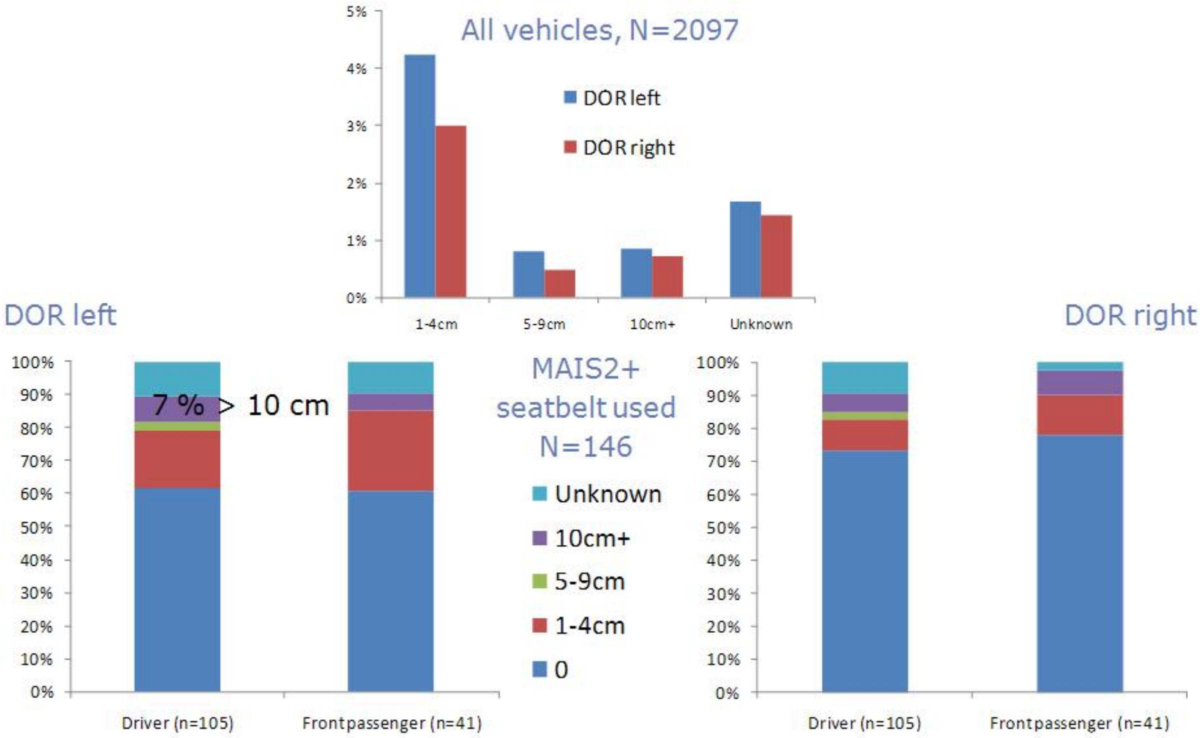


Figure 6.16: Door opening reduction (DOR) for VEHICLE LEVEL (top) and OCCUPANT LEVEL (bottom).

Switching to the OCCUPANT LEVEL and focusing on belted MAIS 2+ occupants led to a total number of n = 146 and to slight differences between DOR on the left and the right side. This is shown in Figure 6.16 as well (two charts below). About 7% of the drivers plus about 5% of the front seat passengers had been severely injured in conjunction with significant door opening reductions of at least 10 cm on the near-side seating position. 60% of accidents with MAIS 2+ casualties have not shown any DOR on the left side, whereas 70% of accidents with MAIS 2+ casualties did not show any DOR on the right side, for both drivers and front passengers.

When analysing the charts and the accompanying statements one has to consider that these analyses focus on frontal collisions with directly opposing force directions. Hence, very often damage occurred to the left and right vehicle sides at the same time. Checks whether one vehicle has damage on both sides have not been conducted.

6.4.3 Frontal Overlap

Frontal overlap in this analysis means the amount of directly damaged (deformed) impact structure overlapping with the collision partner. The value is expressed as a percentage of the vehicle’s width and is split into 25% steps. For example, 20% of overlap by the collision opponent could mean either 20% of the car front is damaged from one edge or some area (20% of the car width) in the central car front has been damaged and the car wings/fenders are undeformed. Looking at the entire data set (VEHICLE LEVEL, n = 2097) some significant differences could be observed, Figure 6.17. The distributions of overlap were very similar between CAR_CAR and CAR_HGV crashes, in contrast to the shares of crashes CAR_OBJ and CAR_OTH. Nearly half of all passenger cars in crashes between two cars showed frontal overlaps of 75 - 100% and two-thirds of all vehicles had overlaps of at least 50%. Most frontal collisions (about 65%) between cars and objects (e.g. narrow objects such as trees) ended up in small overlaps of 1 - 24%. Of course these facts are directly related to the geometry and mass of the collision partners.

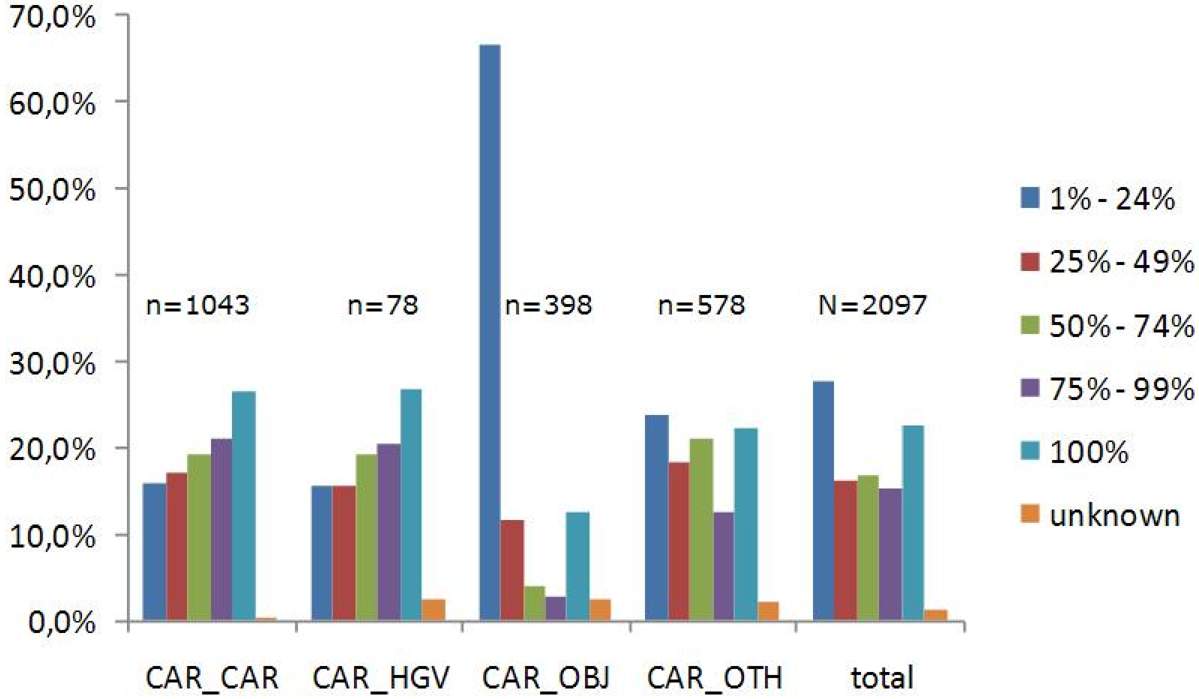


Figure 6.17: Frontal overlap.

Distributions of the injury severities (each category is 100%) against the frontal overlap on OCCUPANT LEVEL (n = 780) are shown in Figure 6.18. The chart considers all collision partner groups; seat belted injured people who survived with a known MAIS were classified into the three categories MAIS 1, MAIS 2+ survived and fatal. The analysis of Figure 6.18 does not list statements concerning fatalities because there are 'only' nine fatalities shared over four overlap steps. Comparable portions between MAIS 1 and MAIS 2+ injured persons could be found over all overlap steps as well as distinctive peaks for low (1 - 24%) and full overlaps (75 - 100%). About 40 - 45% of all injured people suffered from frontal overlaps in the range of 75 -1 00%. The marked red line is a trend line of the MAIS 2+ survived group throughout all overlap steps. In this dataset no MAIS 2+ survived person sustained a MAIS value of 5 or 6.

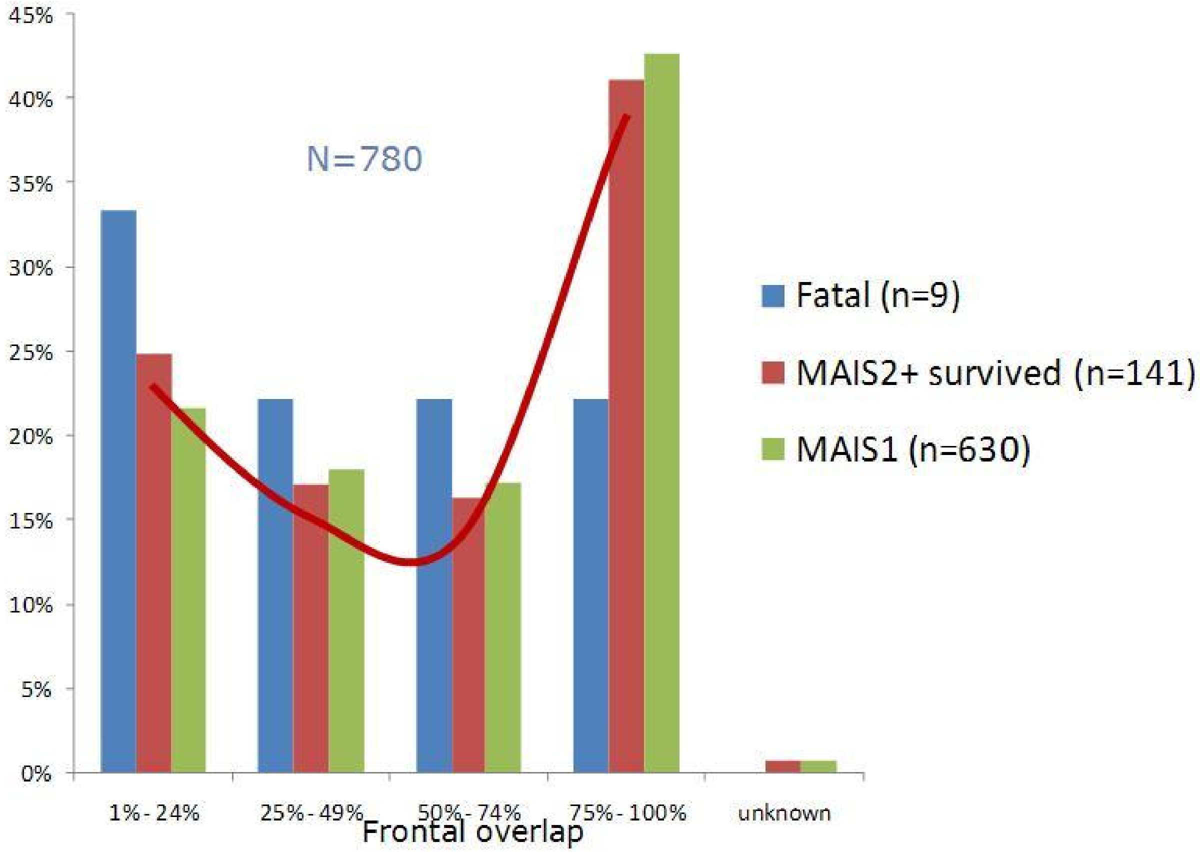


Figure 6.18: Distribution of injury severity against frontal overlap.

Furthermore, Figure 6.19 restricts this dataset to the collision group passenger car against passenger car (n = 534). Two-thirds of all involved injured people occurred at an overlap >50% and nearly half of them at a frontal overlap >75% but only about 20% of these injuries were related to low overlaps (1 - 24%).

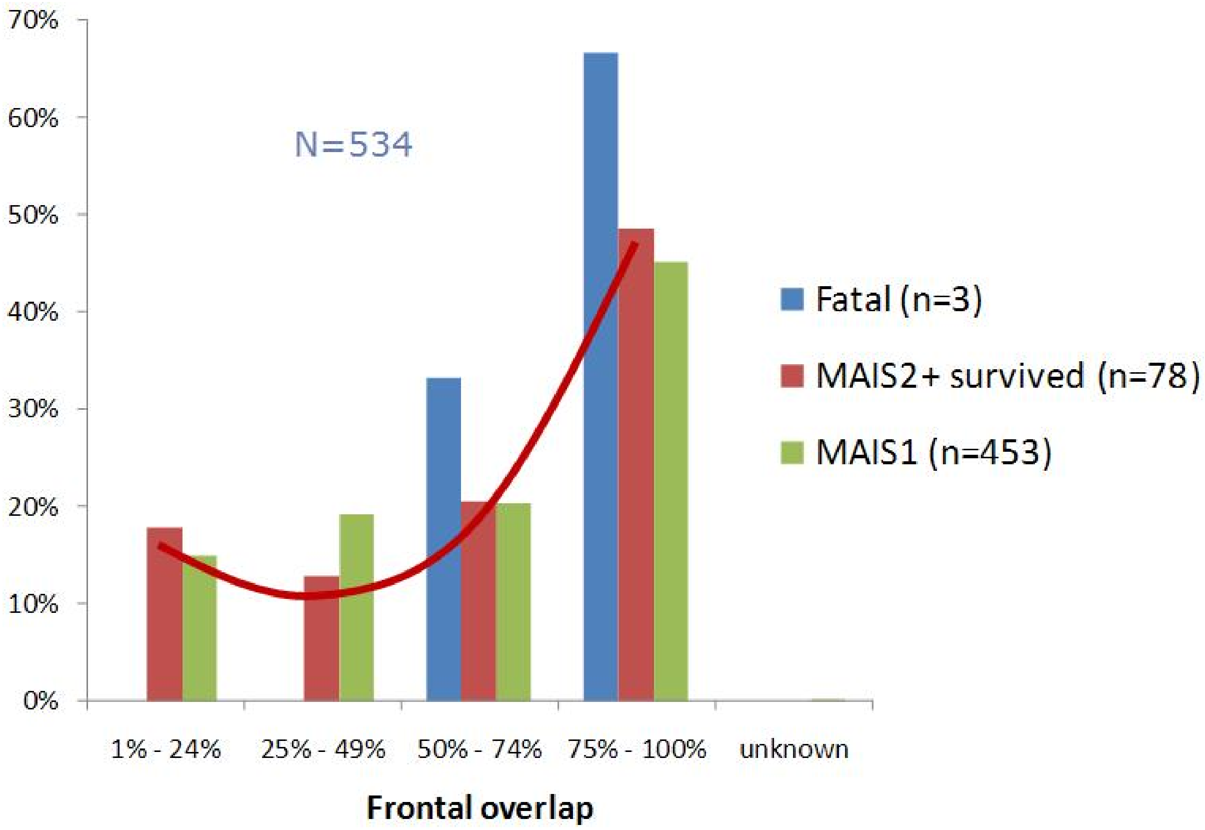


Figure 6.19: Distribution of injury severity against frontal overlap for CAR_CAR.

To give further core statements it would be necessary to consider the frequencies of these frontal overlap steps and to combine them with the information about the injury severities.

Table 11 reveals the shifting of the proportions of the MAIS 2+ injured people (survived, seatbelt used) against the frontal overlap (OCCUPANT LEVEL). Again the trend could be seen that narrow objects (up to a frontal overlap of 24%) were more frequent over all MAIS 2+ cases than for crashes between two passenger cars. In the latter group full frontal overlap crashes were observed more often. In other words, car-to-car crashes often showed less severe issues with low frontal overlap than car crashes with other collision partners such as tree objects.

Table 11: Frontal overlap for known injured, survived people (MAIS 2+), seatbelt used

Frontal overlap	1%-24%	25%-49%	50%-74%	75%-100%
MAIS 2+ (all groups) n = 140	25%	17%	16%	41%
MAIS 2+ (car vs. car) n = 78	18%	13%	20%	49%

6.4.4 Horizontal Location of the Deformation

The VDI3 (Vehicle deformation index 3) codes the specific horizontal location of the damage for all four sides of a vehicle. It is possible to code the damage of the whole front, side or rear just as smaller parts, e.g. from the car wing to the longitudinal beam or the centre part between both longitudinal beams.

In order to evaluate whether or not the impact occurred at the corners or in the centre of the car VDI3 can be analysed. This analysis is especially important for the small overlap cases, where important differences between CCIS and GIDAS were observed. Taking the entire dataset and focussing on the cases that have VDI3 coded as well as on the accidents with at least one MAIS 2+ survived, injured, and belted person led to n = 101 remaining passenger cars (VEHICLE LEVEL). Figure 6.20 shows the VDI3 distributions for different collision partner groups. Most impacts could be seen for the full front width over the groups which had a range from 37 - 45% there. The remaining proportions revealed deviating trends. These proportions were distributed uniformly regarding all groups (n = 101), showed a trend to the left side for crashes between two passenger cars and were mostly centred for collisions of cars and objects like trees.

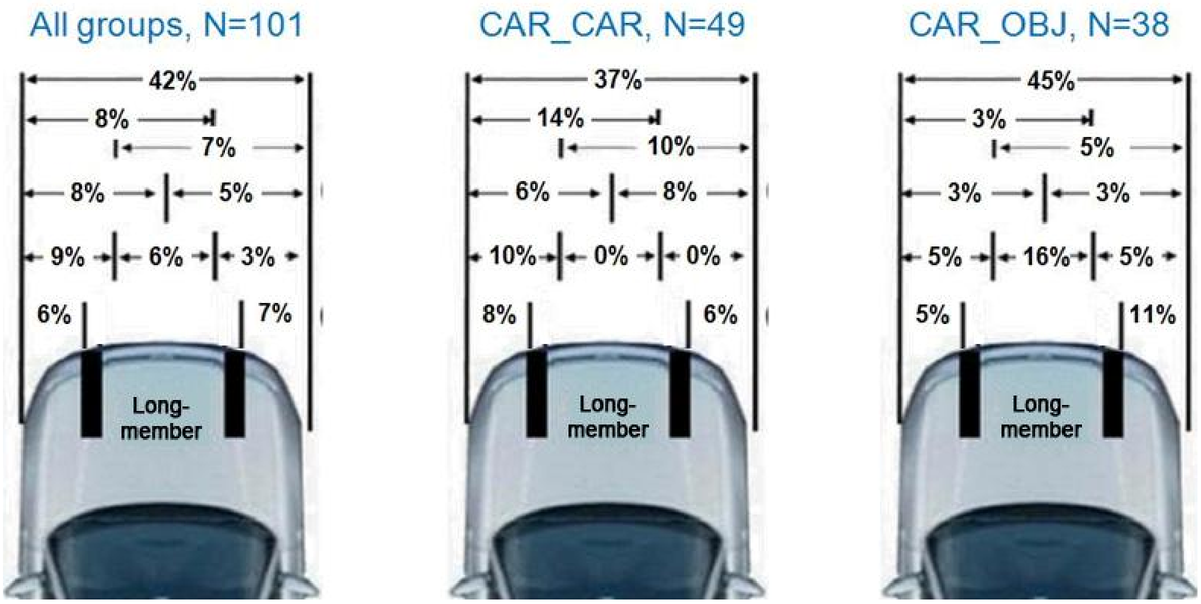


Figure 6.20: VDI3 distributions for all groups, car-to-car and car-object collisions.

By using the VDI3 coding the horizontal frontal car damages could be identified. The 'Low External Overlap' is determined as the zones R0, R1, L0 and L1 (see VDI3 in glossary) which represent the areas from the car wings up to the longitudinal beams on the left and the right side of the front. Transferring these cases to the OCCUPANT LEVEL led to the percentages in Table 12. This table shows the numbers of MAIS 2+ casualties for the different collision partner groups as well as the proportions for the low frontal (external) overlaps within each group. Omitting the crashes CAR_OTH (due to its very small number of cases) led into percentages of 20 - 24% for each collision partner group. That means the low external overlap issue was distributed homogeneously within each group CAR_CAR, CAR_HGV and CAR_OBJ on OCCUPANT LEVEL. Furthermore, nearly each fourth observed person suffered from an AIS 2+ injury following a Low External Overlap crash.

Table 12: Low frontal (external) overlap (from car wing to longitudinal beam)

Low External Overlap (VDI3: 20, 40, 21, 41)	All groups n=141	CAR_CAR n=78	CAR_HGV n=15	CAR_OBJ n=46	CAR_OTH n=2
MAIS 2+ casualties	23,4%	24,3%	20,0%	23,9%	0,0%

6.4.5 Mass

One of the most likely contributing factors to severity of crashes is mass of the opposing vehicle/object in a crash. Therefore, Figure 6.21 shows total numbers of the distribution of all involved vehicles opposite to their kerb weight split into 250 kg intervals on the VEHICLE LEVEL. About 80% of these vehicles were in the kerb weight range of 1000 - 1749 kg and approximately 60% between 1000 kg and 1499 kg.

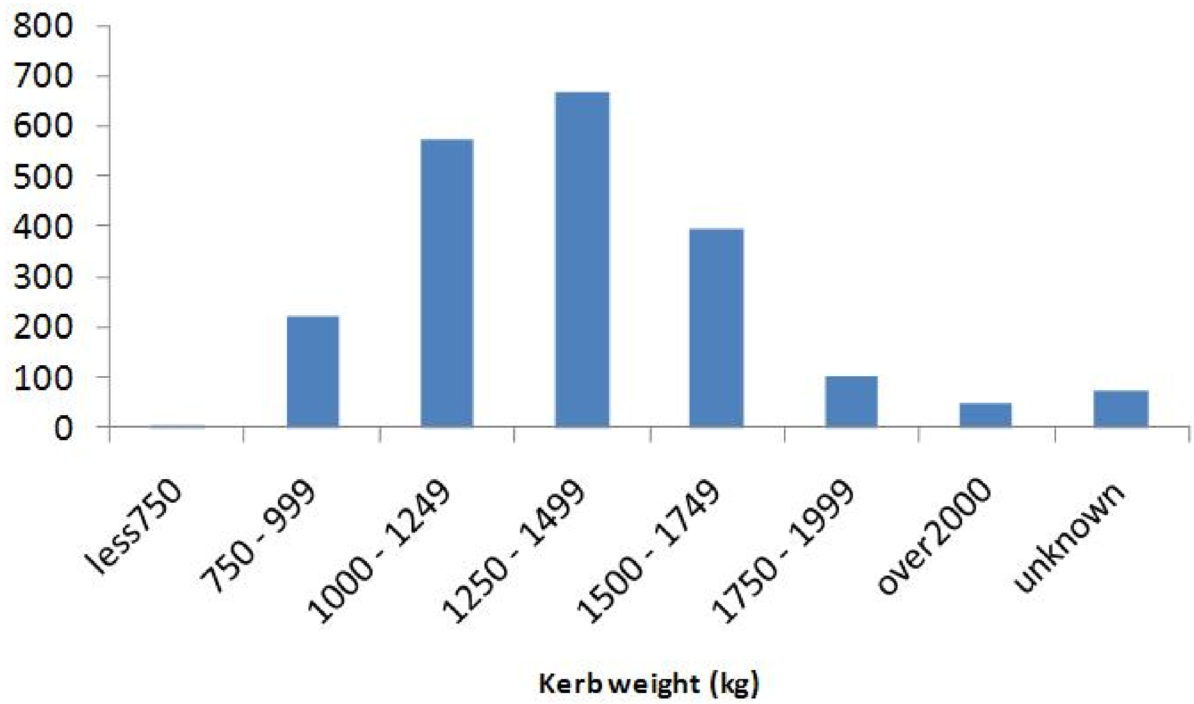


Figure 6.21: Total numbers of vehicles (n = 2097) by kerb weights.

Figure 6.22 presents the linear mass ratio for the reduced sample to crashes between two passenger cars with known injury severities MAIS 2+ and belted occupants on VEHICLE LEVEL (n = 50). This mass ratio was calculated by the division of opponent's and one's kerb weight. That is, when the mass ratio is greater than 1, the opponent car is heavier. Most frequent were crashes with the mass ratios between 0.9 and 1.29 which accounted for approximately half of all cases.

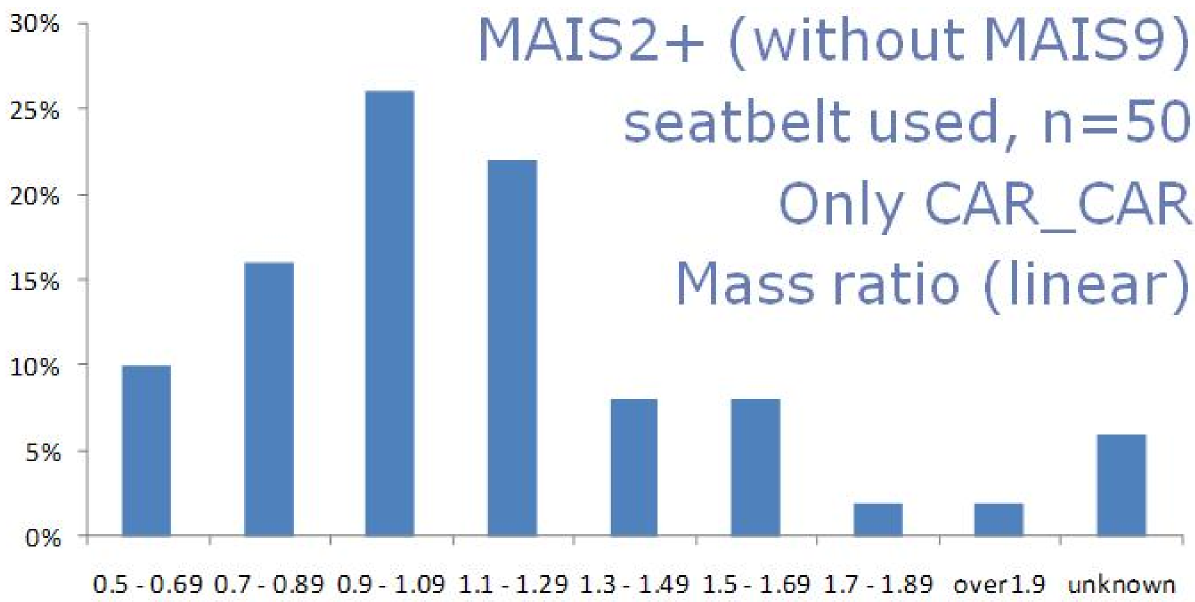


Figure 6.22: Linear mass ratio.

6.4.6 Injury Mechanisms

As a further part of the collision analysis injury mechanisms were identified in the GIDAS sample based on six specific categories that describe possible contact partners which might contribute to severe injuries in time of the crash.

The categories ('Restraint', 'Contact w/o intrusion', 'Contact w intrusion', 'Non-contact', 'Unknown causation of contact', 'Other object') are explained more in detail in Table 13.

Table 13: Explanation of injury mechanisms categories

Category	Explanation and examples
'Restraint'	Restraint system *E.g.: airbags, seat belt (webbing, buckle...), headrest. The categorisation as restraint injury does not imply that there was something wrong with the restraint system or that injury severity would be reduced without the restraint system.*
'Contact No Intrusion'	All parts and items inside the car (no 'Restraint' parts) that are normally fixed. No intrusion to the occupant compartment *E.g.: steering wheel, radio, section of sunroof, air vents, dashboard, pedals, glass between pillars...*
'Contact Intrusion'	All parts and items inside the car (no 'Restraint' parts) that are normally fixed. Intrusion to the occupant compartment
'Non-contact'	Own actions (*e.g. bit tongue*) or body motions, Rescue measures Fire
'Unknown causation'	Unknown
'Other object'	All remaining parts and items inside the car and from outside (no 'Restraint', 'Contact No Intrusion', 'Contact Intrusion' parts). *E.g.: interaction between passengers, ejected, collision partner, crash barrier, road surface, front spoiler...*

A specific analysis is shown in Figure 6.23 on OCCUPANT LEVEL (n = 141) to discover injury causing effects of intruding car parts or items, the restraint system, other objects and other causations within all collision partner groups. This chart considers belted MAIS 2+ survived occupants. Within this sample the single most severe injuries (AIS 2+) by body region were investigated in order to identify their coded main causation and assigned to the six categories. If a person sustained several injuries with the same highest AIS value in the same body region, one injury was chosen by choice. It could be identified that only few injuries were caused by contact with intruding parts (12%), but more than 40% of these injuries were caused by both the restraint system and normally fixed car-internal parts. Of course, in case of unknown causation these numbers could increase slightly.

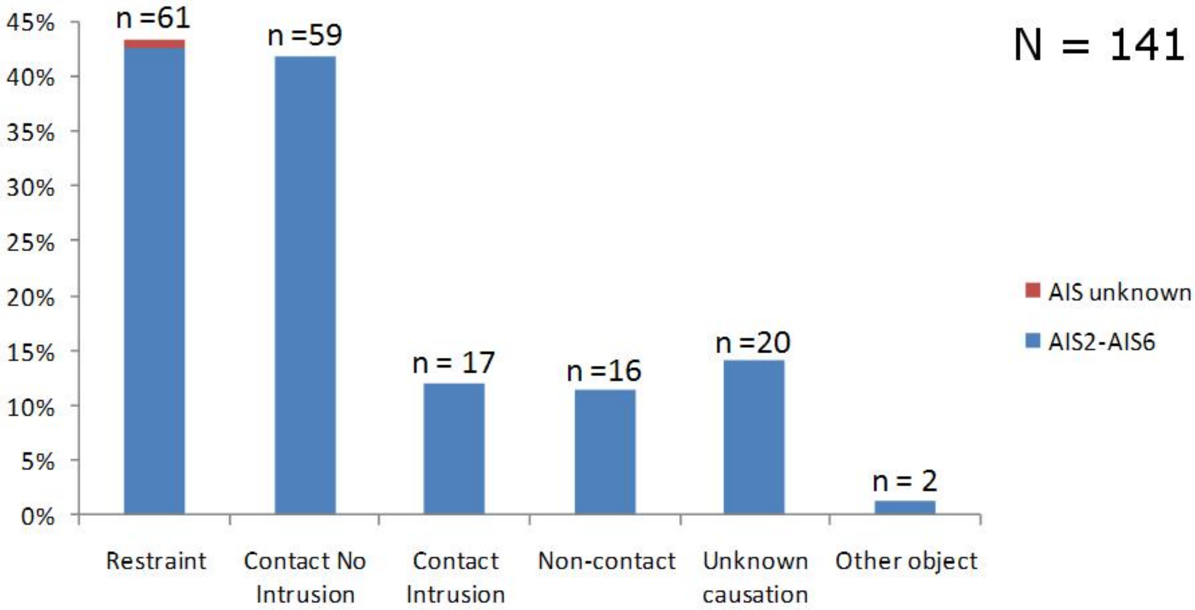


Figure 6.23: Injury mechanisms

The same dataset was used to show the differing proportions (see Figure 6.25) for the frontal overlap reduced by one case due to missing information. Each frontal overlap group is 100% (and hence all times n = 140) which means these groups can be compared with each other. For each of these groups the causations of the injuries are shown in the classification of AIS 2 - AIS 6 in percentage. The remaining percentages (not shown in Figure 6.25) per combination could be assigned to AIS 0 - AIS 1. Only within the combination overlap of '25% - 49%' and injury causation 'Restraint' 4% of the AIS data was unknown and is also not shown in Figure 6.25. It could be seen that the proportions of injuries caused by 'Restraint' increased with higher overlap and that injuries caused by 'Contact intrusion' decreased with higher overlap.

The analysis in section 6.4.4 and in particular the results of Table 12 identified that approximately 23% (n = 33) of the MAIS 2+ casualties (n = 141) could be allocated to crashes with low external overlap. This low number of low external overlap cases (n = 33) is analysed for the injury causation in Figure 6.24. Again, serious injuries (AIS 2 - AIS 6) caused by 'Restraint' could be identified as most frequently occurring injuries.

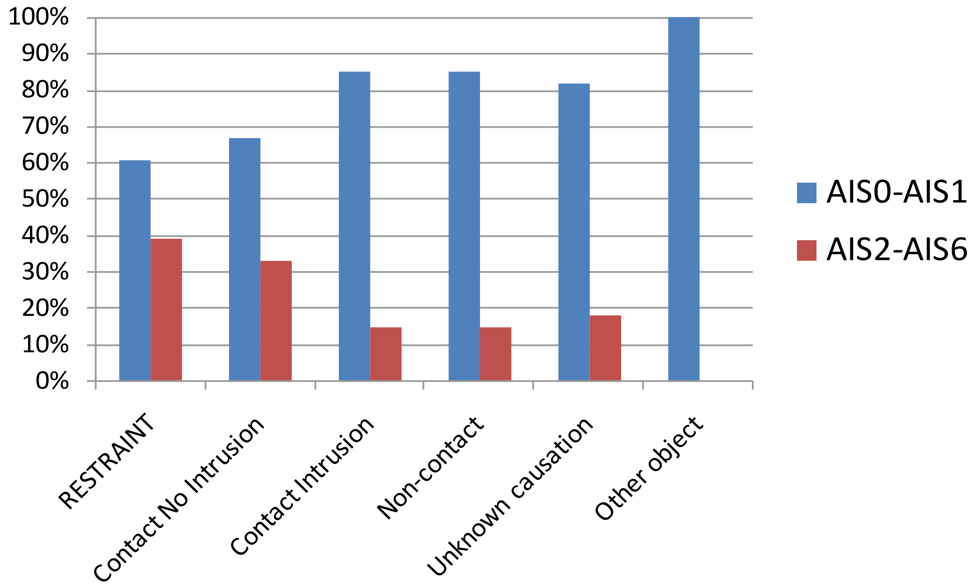


Figure 6.24: Injury causations in low external overlap cases.

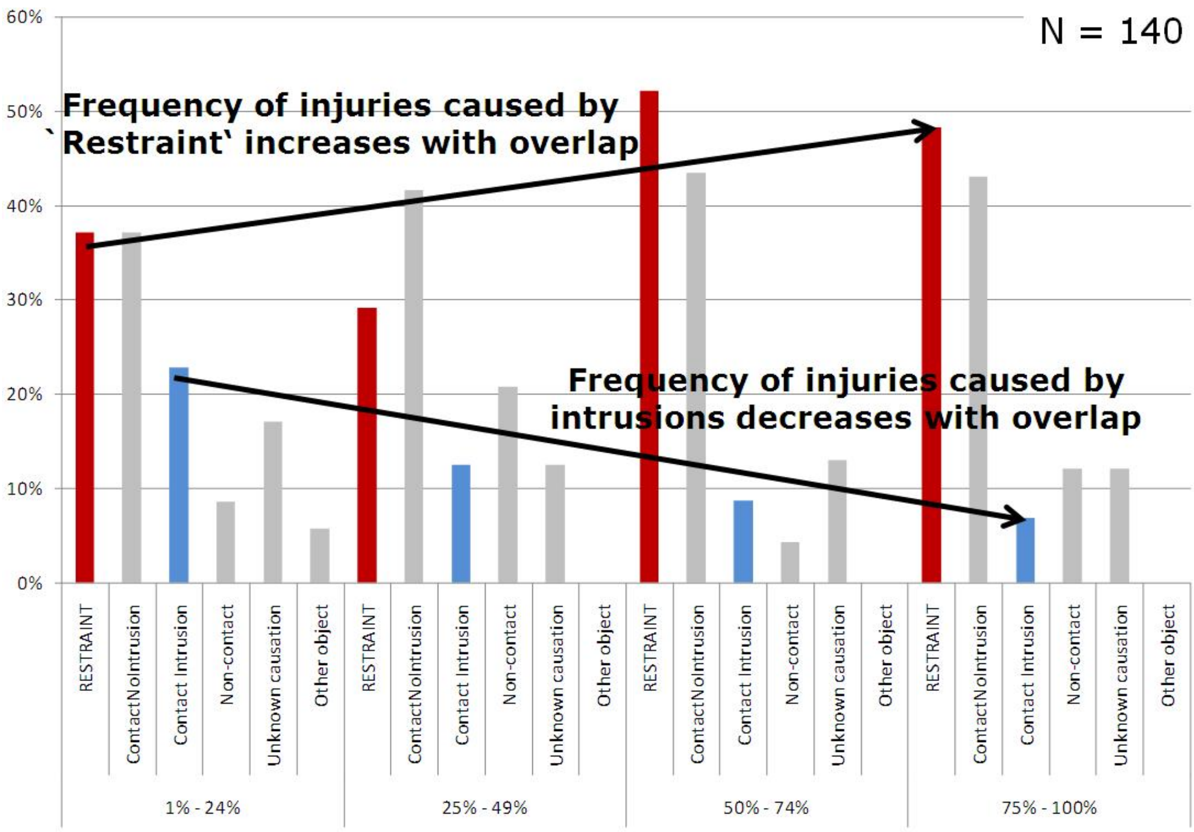


Figure 6.25: Proportions of AIS 2+ injuries by frontal overlap groups for crashes CAR_CAR (each combination of frontal overlap and injury causation group represents 100% - missing percentages are assigned to AIS0, AIS 1 and unknown injury severity).

6.4.7 Acceleration Loading

This section investigates the acceleration loading to the occupants for different core parameters and the restriction to serious injuries (MAIS 2+ injured, survived people) independent on their injury causations as in the previous sections. It is important to mention that due to the created injury causation groups the acceleration issues were exclusively referred to 'Restraint'. The AIS levels shown in this section refer to these acceleration caused injuries. Further injuries or causations were not considered detailed in this section. The following paragraphs are on INJURY LEVEL. If no injury of an occupant was assigned to the 'Restraint' group, AIS 0 was assigned.

6.4.7.1 Frontal Overlap

Focussing on the injured individuals with known frontal overlap (n = 140) led to the distributions demonstrated in Figure 6.26. Each column represents one frontal overlap group that summarise the respective cases to 100%. With the help of this chart serious injuries caused by 'Restraint' could be identified to occur more often in cases of higher overlap (>50%). Again, a frontal overlap of 50% could either be beginning on a side of the car or could be centred in the front or something in between.

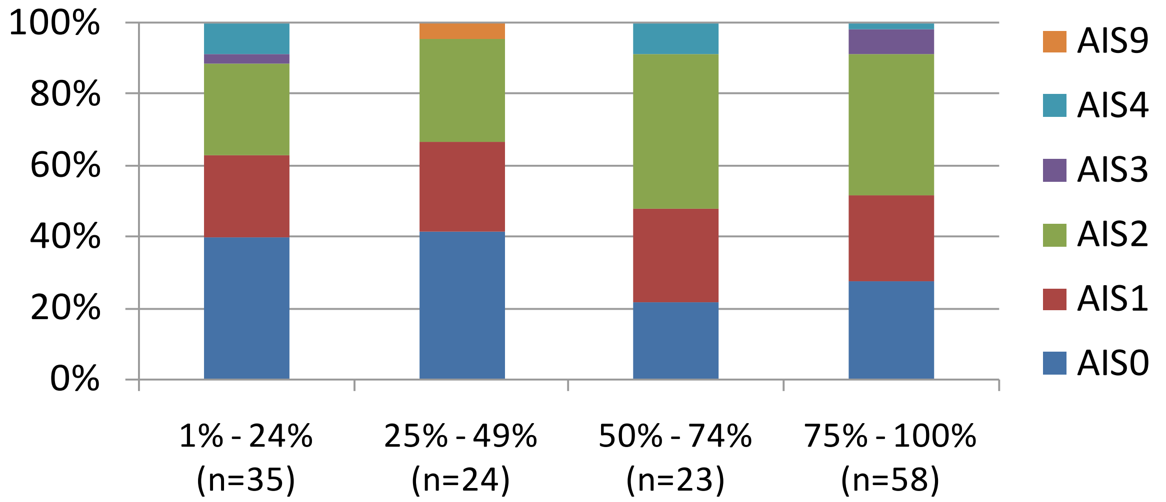


Figure 6.26: Injuries caused by 'restraint' by frontal overlap (AIS 0: other injury causation group).

6.4.7.2 Collision Partner

A further analysis parameter is the kind of collision opponent. Figure 6.27 shows the proportions of the acceleration loading caused injuries by each group (each 100%). Serious injuries (AIS 2+) due to 'Restraint' were most frequent in collisions between two passenger cars and cars against heavy good vehicles.

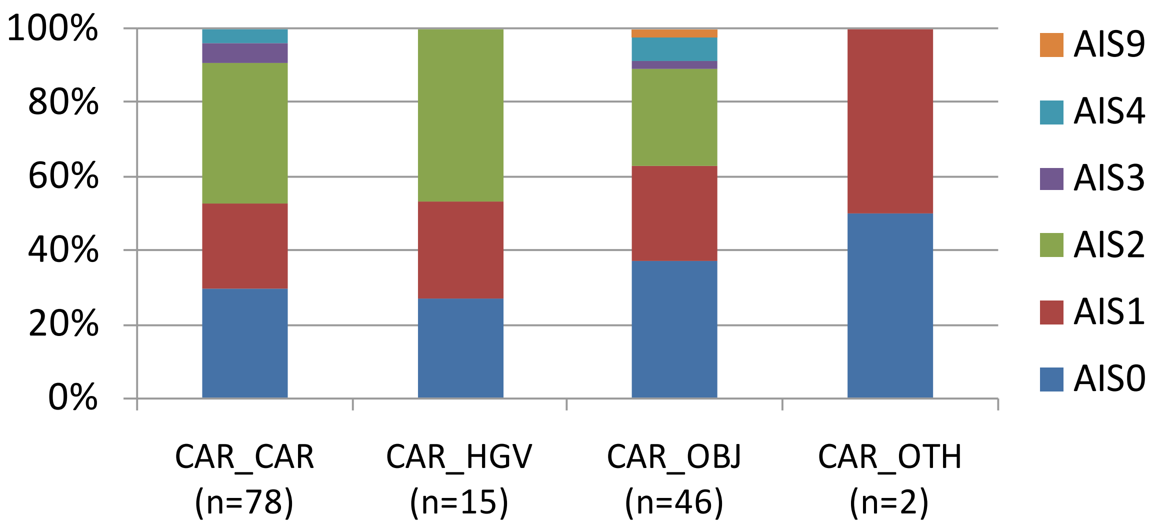


Figure 6.27: Injuries caused by 'restraint' by collision partner groups (n = 141) (AIS 0: other injury causation group).

6.4.7.3 Mass Ratio

The kerb weight ratios of the vehicles are shown in Figure 6.28 whereby each column is 100%. Because of the fact that this value could only be calculated for crashes between one passenger vehicle and another vehicle the total number of used (known) mass ratios was n = 76. Serious injuries due to 'Restraint' were more frequent in cases when the opponent car is heavier.

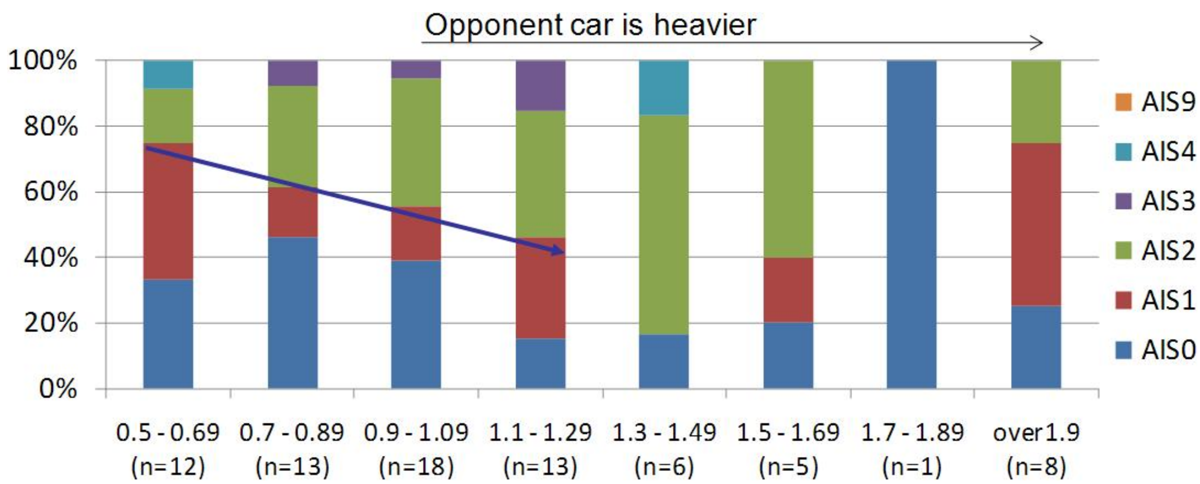


Figure 6.28: Injuries caused by 'restraint' by mass ratios (n = 76) (AIS0: other injury causation group).

6.4.7.4 Age Groups

The age was known of all concerned people (n = 141) and classified into the five groups already used in Chapter 6.2. In this analysis no clear trend could be identified for serious injuries due to 'Restraint' as can be seen in Figure 6.29.

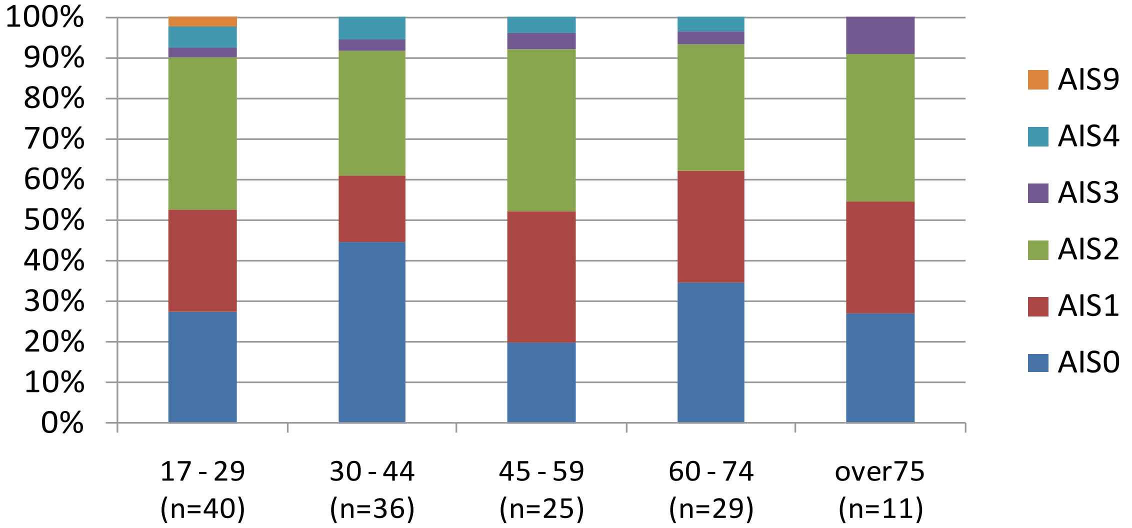


Figure 6.29: Injuries caused by 'restraint' by age groups (n=141) (AIS0: other injury causation group).

6.4.7.5 Gender / Seating Position

As introduced in Section 6.2 the gender might be a meaningful parameter and is shown together with the seating positions in Figure 6.30. In general, serious injuries (AIS 2+) due to 'Restraint' showed higher proportions for women than men. Having a look at their seating position led to the finding that serious injuries due to 'Restraint' are linked with slightly higher proportions for front passengers than drivers. This could also be analysed in combination with the gender but this would decrease the dataset too much and therefore no numbers are presented.

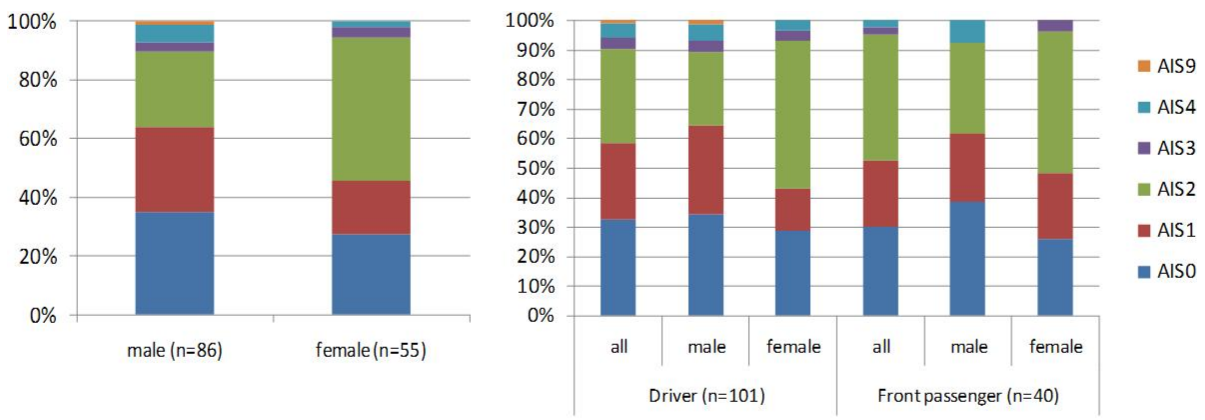


Figure 6.30: Injuries caused by 'restraint' by gender and seating position (AIS 0: other injury causation group).

6.4.7.6 Stature

The same dataset was used to make an analysis about the body stature. The number of cases is reduced to n = 103 (see Figure 6.31) since the information was not always available. Each column represents one stature group (each is 100%). Serious injuries (AIS 2+) due to 'Restraint' revealed higher proportions for smaller people (under 170 cm). In contrast, when 'Restraint' injuries occurred in taller occupants the injuries tended to be more severe.

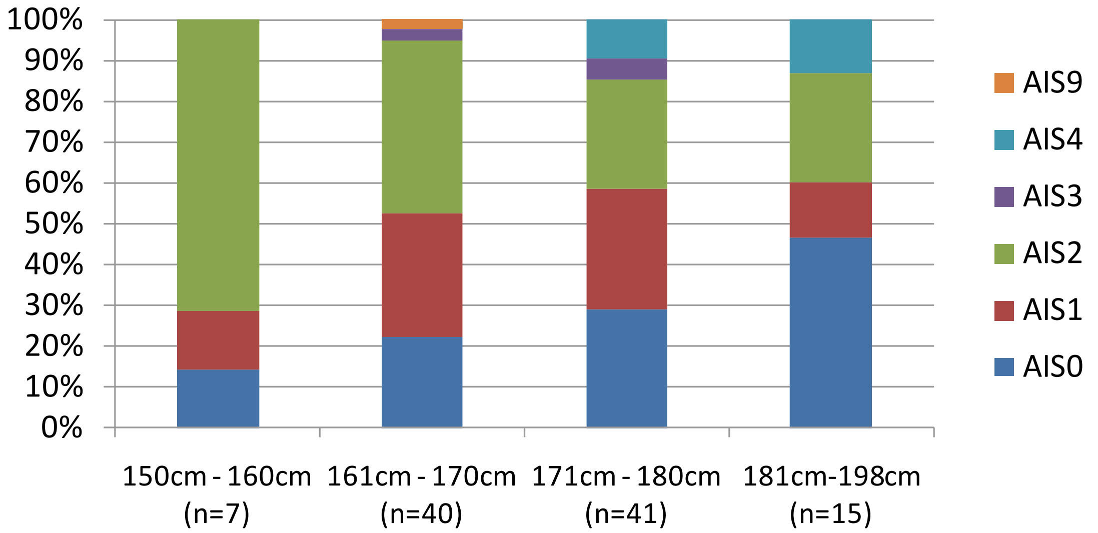


Figure 6.31: Injuries caused by 'restraint' by stature (AIS 0: other injury causation group).

6.4.7.7 Body Weight

Another parameter analysed was the body weight which could be used in n = 104 cases and is shown in Figure 6.32. The weight was classified into 6 categories. No clear trend could be identified for serious injuries due to 'Restraint'.

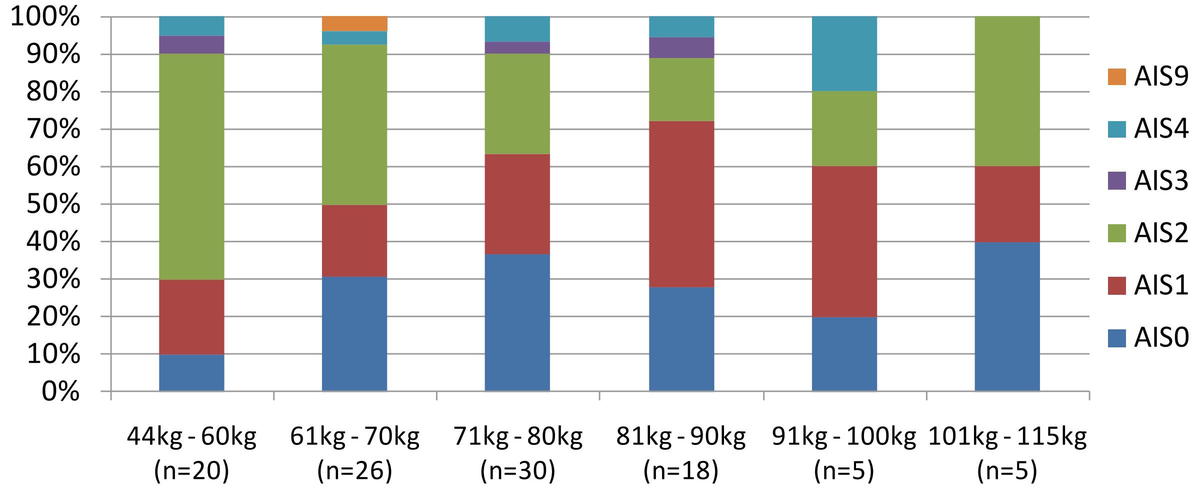


Figure 6.32: Injuries caused by 'restraint' by body weight (AIS 0: other injury causation group).

6.5 Conclusions GIDAS Analysis

The analyses often considered the collision partner groups (see Table 7). Most frequent collisions occurred between two passenger cars (CAR_CAR), followed by crashes of cars with others (CAR_OTH) and objects (CAR_OBJ). In contrast, the highest probability for an occupant to sustain severe injuries or even to die was for passenger car crashes against objects (CAR_OBJ) or heavy good vehicles (CAR_HGV). Most crashes occurred with an EES below 50 km/h.

Stability loss of a-pillar, bulkhead or dashboard could be identified in about 10% of all crashes between passenger cars and heavy good vehicles (CAR_HGV) and 5% in collisions of cars against objects (CAR_OBJ). Regarding all frontal crashes between two passenger cars (CAR_CAR) about 2% showed stability losses, increasing to 10% when focusing on accidents with a high injury severity outcome.

The injury frequencies and probability of occupants rose with high overlap (> 75%) likely due to acceleration and in contrast, by small overlap (< 25%) likely due to intrusion. This higher injury risk in crashes with low and full overlaps could be assigned to all collision groups. Table 14 shows some noticeable issues related to overlap.

Table 14: Noticeable issues on injury frequencies and risks

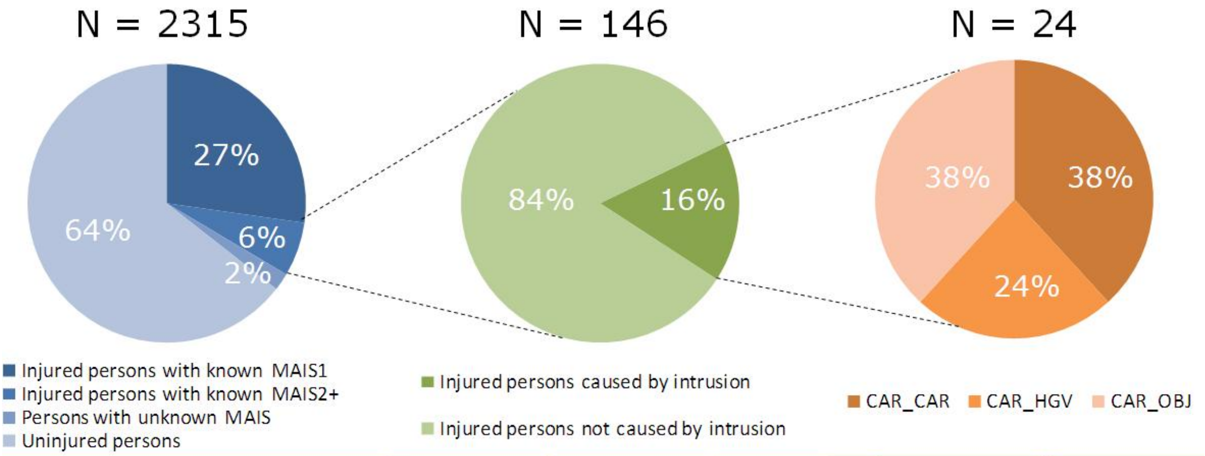
Collision partner group	Noticeable issues
'CAR_CAR'	• High injury risk in crashes with full overlap • Few cases of deformed a-pillars, bulkheads and dashboards
'CAR_OBJ'	• Frequent collisions with low overlap and not activated main load paths • Severe injuries caused by high deceleration (also in collisions without compartment intrusions)

Poor structural interaction was observed in low overlap crashes of passenger cars against another passenger car (CAR_CAR) or against an object (CAR_OBJ), as well as in collisions of a car and a heavy good vehicle (CAR_HGV).

If there was a severe frontal crash, passenger car occupants sustained most frequent injuries on their thorax and head. These injuries were often related to acceleration issues (e.g. restraint systems) and just few to intrusions.

Figure 6.33 shows the GIDAS sample on OCCUPANT LEVEL restricted to belted people (n = 2315). Extracting the injured people with known MAIS 2+ led finally to 146 people. 16% of these MAIS 2+ injured people sustained serious injuries that were mainly caused by intruding parts. The third circle diagram in Figure 6.33 bases on these crashes including injured occupants who sustained injuries caused by intrusion into the car, classified by the collision partner groups (n = 24).

The table within Figure 6.33 represents the first and second circle diagram and shows the percentages of the collision partner groups based on the injured people with known MAIS 2+ injury level.



FREQUENCIES	CAR_CAR	CAR_HGV	CAR_OBJ	CAR_OTH	Total N
Known MAIS2+, seat belted	55%	12%	32%	1%	146
Injured persons caused by intrusion	38%	24%	38%	0	24

Figure 6.33: Overview on seat belted, injured people caused by intrusions.

Furthermore, CAR_CAR crashes showed a higher injury frequency of MAIS 1 compared to collisions of type CAR_OBJ. In contrast injuries with MAIS 2 and MAIS 3 could be more frequently assigned to crashes of type CAR_OBJ than to car-to-car (CAR_CAR).

Additionally, some further occupant characteristics could be identified. Higher injury risks could be detected for female (especially AIS 1 and AIS 2 injuries), for elderly people and for front seat passengers.

Additionally, serious injuries (AIS 2+) due to acceleration loading (here restricted to causation group 'Restraint') could be identified with higher proportions in:

- Crashes with higher frontal overlap (>50%),
- Collisions CAR_CAR and CAR_HGV,
- Cases when the opponent vehicle is heavier and in
- Cases of smaller people.

7 EUROPEAN ACCIDENT ANALYSIS

The original analysis of frontal impacts in the PENDANT was restricted by decisions taken by the consortium in the first months of the project. Although PENDANT contains about 150 frontal impacts, very few of them comply with the selection criteria of UNECE R94 compliant vehicles. As a result there were only 5 cases that were possible for detailed analysis. Of these, some cases were already included in the CCIS analysis. However, the overall analysis of PENDANT database gives additional input to FIMCAR and is summarised below.

The PENDANT database was quickly analysed to provide impact data that was not dependent on the vehicle age. The following analyses do not account for impact severity or injury outcomes and provide a reference for all types of frontal impacts.

The overlap of frontal impacts (all impact types) was reviewed to provide information important for the test configuration. In Figure 7.1, the PENDANT researchers reported that about 50% of frontal impacts had an overlap of 50% or less.

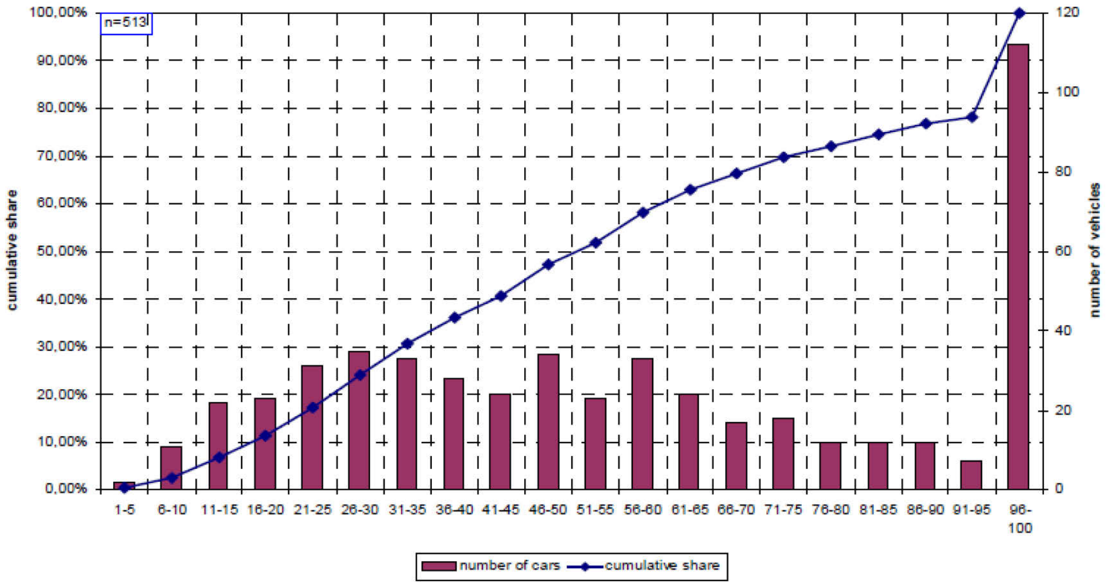


Figure 7.1: Vehicle overlap as reported by PENDANT consortium.

Further analyses of the car-to-car frontal impacts that were present together with their accident reconstructions results were conducted within FIMCAR. This provided a dataset of 166 vehicles spanning all model years.

Figure 7.2 shows how frontal crashes can be grouped into PDOF and impact severity using calculated delta-v. The figure shows that impacts with low delta-v (< 30 km/h) are most often angled impacts (11 o'clock) higher delta-v collisions are most frequently straight-on frontal impacts.

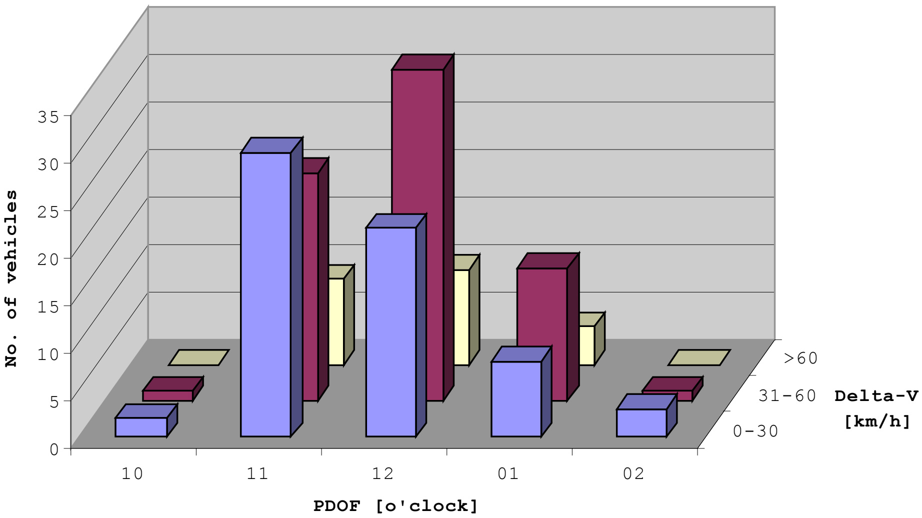


Figure 7.2: Principal direction of force in different delta-v intervals (n = 166). Compensated for right hand driven cars.

Figure 7.3 shows how often a certain horizontal overlap occur for different delta-v intervals. Because of the reasonable symmetry in the front structure of cars, left and right are combined for the different horizontal locations in terms of driver side impacts.

In general one can see that the horizontal location of the impact and the PDOF share similar characteristics. More central impacts and straight-on (12 o'clock) impacts are common for higher severities (delta-v > 60 km/h). At lower speeds, the distribution of horizontal location is more to the left and is consistent with the large number of 11 o'clock impact directions. This is an expected result for left turning conflicts.

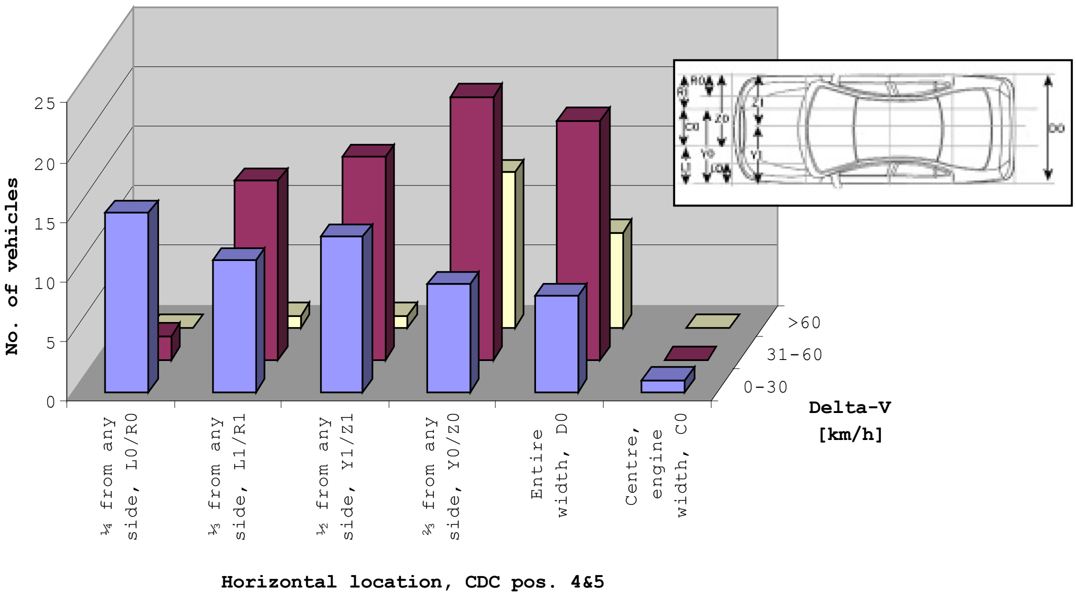


Figure 7.3: Horizontal location of direct contact for different delta-v intervals (n = 156). Only impacts with CDC3="front".

8 DISCUSSION

As detailed in Section 4, the accident sampling procedures for the GB CCIS and German GIDAS databases are different. The CCIS sampling procedure is biased towards accidents containing fatal and seriously injured (MAIS 2+ survived) occupants whereas the GIDAS procedure samples accidents involving personal injury to be representative of the national data. The result of this is that the CCIS database contains a greater number of accidents with fatal and seriously injured occupants relevant to this study than the GIDAS database (Table 15).

Table 15: Size of CCIS and GIDAS data samples for study. Note: selection criteria: Regulation 94 compliant (or equivalent) car involved in frontal impact.

Database	Fatal	MAIS 2+ survived (Seriously injured)	MAIS 1 (Slightly injured)
CCIS	83	466	1236
GIDAS	16	156	701

Hence, the approach followed for the study was to focus on the analysis of the CCIS database because the results were more statistically significant due to the larger number of relevant cases. Following this, where possible, a comparison of the results of the CCIS and GIDAS analyses was made to check the relevance of the conclusions of the CCIS analysis (effectively for GB) to Germany and identify any differences.

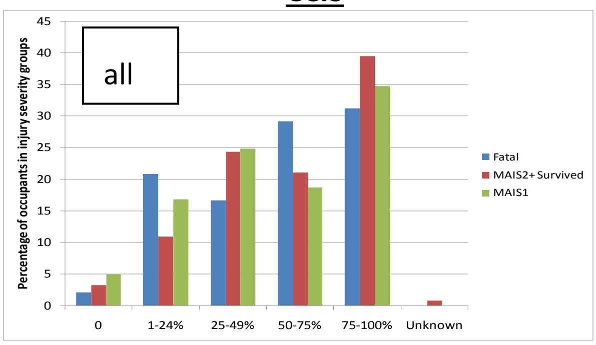
The following key similarities / differences were found:

- Characteristics of data set

  Injury distribution by overlap

  Both the CCIS and GIDAS data show that a high proportion of fatal and MAIS 2+ survived occupants were in crashes with a high frontal overlap (> 75%) (Figure 8.1). However, the GIDAS data for all impacts also shows a slighter higher proportion of fatal and MAIS 2+ survived in lower overlap impacts (< 25%) whereas the CCIS data does not. It is believed that the main reason for this difference is that the GIDAS data includes impacts with narrow objects (e.g. trees and poles), of which there are many in Germany, in the '1 - 24%' overlap category. In contrast the CCIS data includes impacts with narrow objects, of which there are not so many in GB, in a '0' overlap category. Comparison of the injury distribution by overlap for GIDAS car-to-car impacts (Figure 8.2) shows a more similar distribution to the complete CCIS data set.

CCIS



GIDAS

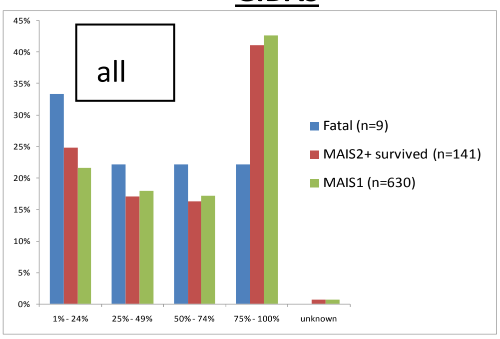


Figure 8.1: Comparison of injury distribution by overlap (belted occupants) for CCIS (left) and GIDAS (right) accident data samples.

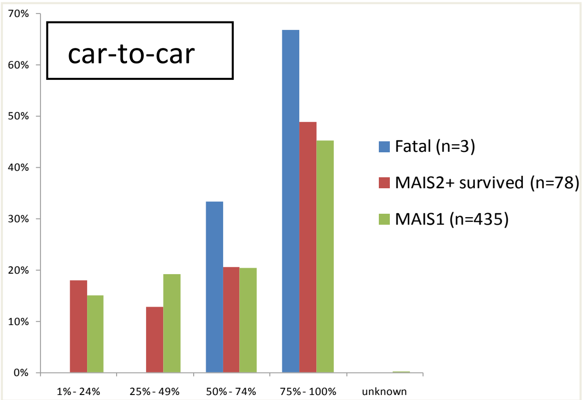
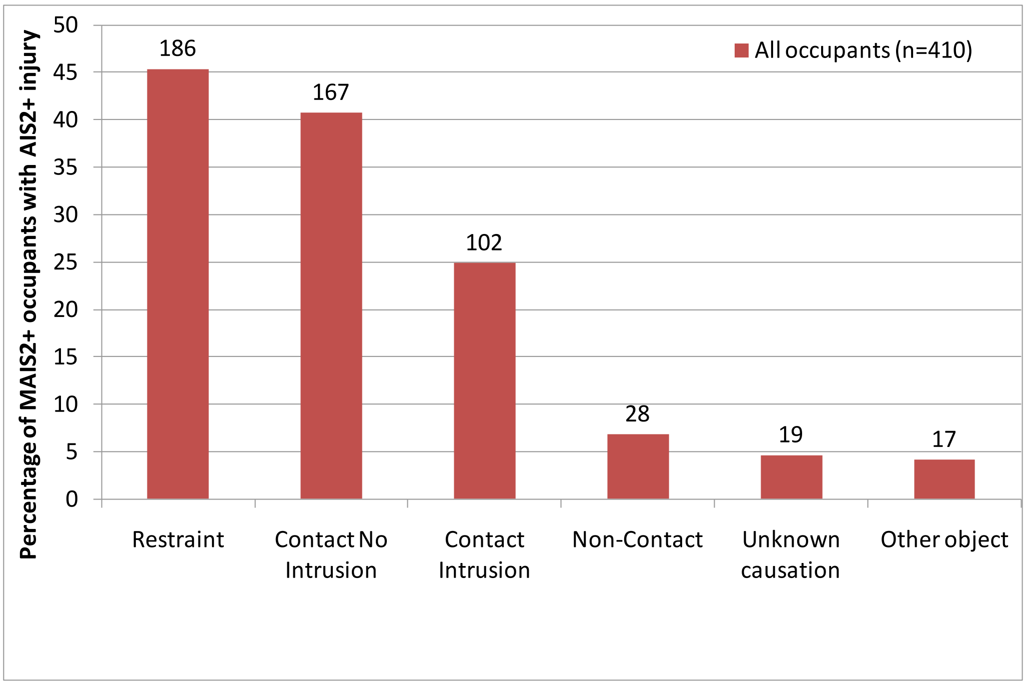


Figure 8.2: Injury distribution by overlap (belted occupants in car-to-car accidents) for GIDAS accident data sample.

- Compartment strength - intrusion

  Injury causation

  For MAIS 2+ injured occupants the proportion of occupants with AIS 2+ injuries caused by contact with intrusion is greater for the CCIS analyses than for the GIDAS analyses (CCIS 25%, GIDAS 12%) (Figure 8.3). Although both studies give different results (which could be caused by the different way of coding of intrusion) both datasets indicate that the compartment strength issue is important in terms of MAIS 2+ injured occupants.



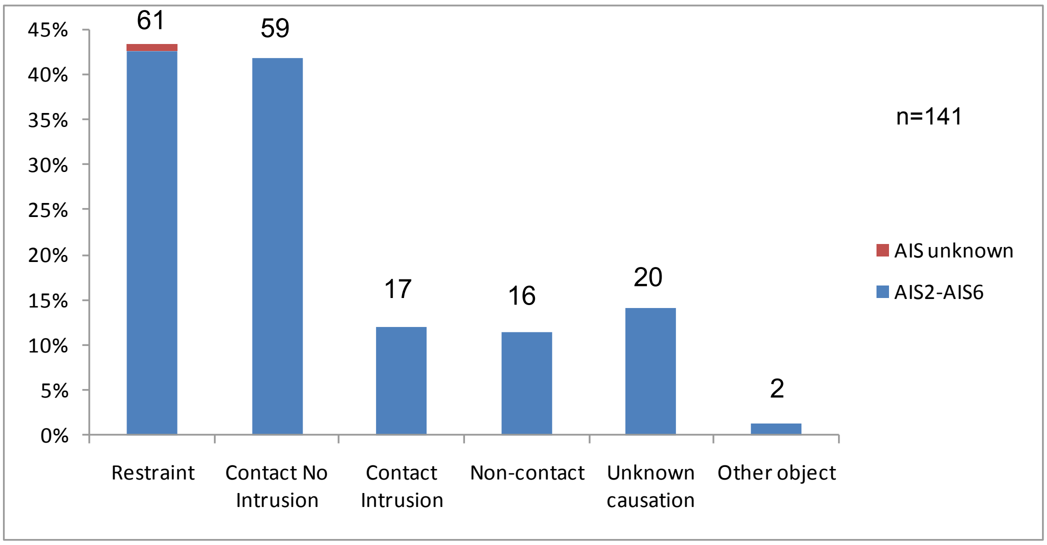
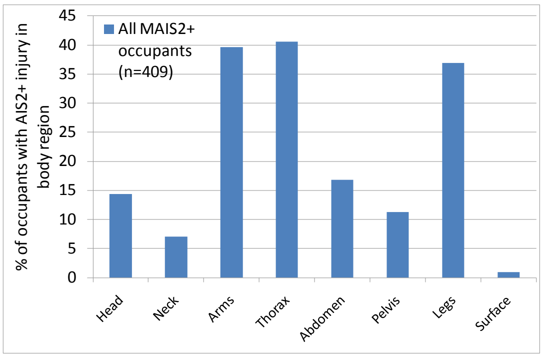


Figure 8.3: Comparison of injury causation for MAIS 2+ injured casualties for CCIS (top) and GIDAS (bottom) accident data samples.

- Injury patterns

  Injury distribution by body region

  For MAIS 2+ injured occupants, for both the CCIS and GIDAS analyses, the thorax is the most frequently injured body region at the AIS 2+ level. However, for the GIDAS analysis the head is almost at the same level as the thorax whereas for the CCIS analysis it is substantially lower. It has not been possible to determine a reason for this difference. AIS 2+ injuries are also frequently sustained to the legs and arms.



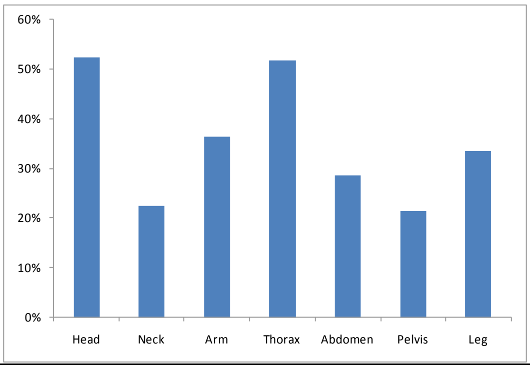


Figure 8.4: Comparison of AIS 2+ body injury distribution for MAIS 2+ injured occupants for CCIS (left) and GIDAS (right) analyses.

9 SUMMARY OF CONCLUSIONS

The main data sources for this report were the CCIS and Stats 19 databases from Great Britain and the GIDAS database from Germany. The different sampling and reporting schemes for the detailed databases (CCIS & GIDAS) sometimes do not allow for direct comparisons of the results. However the databases are complementary – CCIS captures more severe collisions highlighting structure and injury issues while GIDAS provides detailed data for a broader range of crash severities. The following results represent the critical points for further development of test procedures in FIMCAR.

9.1 Compatibility Issues

Poor structural interaction has been observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.

In CCIS structural interaction problems were identified in 40% of fatal and 36% of MAIS 2+ injured cases. However, it is only in cases where there was intrusion present (25% of fatal and 12% of MAIS 2+ cases) that it can be said definitely that improved structural interaction would have improved the safety performance of the car. This is because in cases with intrusion improved structural interaction will increase the energy absorption capability of the car's front-end and thus reduce the intrusion. This, in turn, will help decrease the casualty's injuries caused by contact with intrusion. In cases without intrusion improved structural interaction will change the shape of the compartment deceleration pulse which may or may not help decrease the casualty's injuries depending on the response of the restraint system.

In GIDAS poor structural interaction could mostly be observed in low overlap crashes against objects / cars and in collisions with HGV.

It should be noted that in 23% of the CCIS fatal cases the accident severity was so high that it was not possible to determine whether or not a compatibility issue had occurred.

Frontal force and/or compartment strength mismatch issues between cars in the current fleet appear[6] to be less of an issue than poor structural interaction.

In CCIS, for all accidents, force and/or compartment strength mismatch problems were identified for 8% of fatal and 2% MAIS 2+ survived occupants in CCIS. However, it should be noted that force and/or compartment strength mismatch problems can only be objectively identified for accidents in which there is compartment intrusion into the vehicle.

For car-to-car impacts force and/or compartment strength mismatch problems identified for 9% of fatal and 3% MAIS 2+ survived occupants.

Compartment strength of vehicles is still an issue in the current vehicle fleet.

- Occupants with injuries caused by contact with intrusion CCIS 25%, GIDAS 12% of MAIS 2+ injured occupants.

[6] Note: structural interaction problems could be masking frontal force mismatch problems

    - When an occupant sustains an injury caused by ‘contact with intrusion’ in the majority of cases it is the most severe injury, often a leg or thorax injury but sometimes a head or arm injury.
- In a matched pair analysis of car-to-car impacts from CCIS, a relationship was found between mass ratio and driver injury severity, namely the higher the mass ratio the higher the driver injury severity. However, no such relationship was found between mass ratio and intrusion. The implications of this are that intrusion (and hence compartment strength) is not the major contributory factor to more severe injuries in the lighter car in a car-to-car impact. However, it should be noted that the data sample used for this analysis was relatively small and hence confidence in this result is limited. In addition the result may have been confounded by the age of the vehicle (newer vehicles generally have better compartment integrity) and the age of the occupant.
- Compartment strength is a particular problem in collisions with HGVs and objects, with these collisions having a high proportion of fatal and MAIS 2+ injuries
    - In CCIS, 31% of car-HGV cases resulted in intrusion in the car, compared to 25% for car-to-car cases
    - In GIDAS, 20% of car-HGV cases had MAIS 2+ injury severity for the car occupant, compared with 7% for car-to-car cases

9.2 Injury patterns

- AIS 2+ injuries to the thorax are the most prevalent. AIS 2+ injuries are also frequently sustained by the head, legs and arms.
    - Over 80% of fatally injured occupants and 35% of MAIS 2+ survived occupants sustained AIS 2+ thorax injuries in CCIS
- AIS 2+ injuries resulting related to the restraint system (i.e. those caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injury by contact with other car interior structures) are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not.
    - Over 40% MAIS 2+ occupants sustained AIS 2+ injury attributed to restraint loading in both CCIS and GIDAS datasets.
- Analysis of injury mechanisms in CCIS found that 45% of MAIS 2+ injured occupants had an AIS 2+ injury related to the ‘restraint system’, 40% had an AIS 2+ injury caused by ‘contact with no intrusion’ and 25% had an AIS 2+ injury caused by ‘contact with intrusion’ In the majority of cases these injuries were the most serious injuries that the occupant had.
    - When the most severe injury was related to the ‘restraint system’ the injury was mainly to the thorax (62%) with some to the arms (21%) (clavicle fractures).
    - When the most severe injury was related to the ‘contact no intrusion’ the injury was mainly to the legs (42%) with some to the arms (30%) (clavicle fractures) and thorax (12%).
    - When the most severe injury was related to the ‘contact with intrusion’ the injury was mainly to the legs (46%) and thorax (30%).
- For accidents for which there is intrusion, for MAIS 2+ injured occupants AIS 2+ injuries to the legs are the most prevalent

   - Where intrusion was present about 70% MAIS 2+ occupants sustained AIS 2+ leg injuries in CCIS
   - Note: about 40% sustained AIS 2+ thorax injuries
- AIS 2+ injuries resulting from contact with the intrusion occur in a large proportion of cases where compartment intrusion is present
   - 65% of MAIS 2+ occupants in cars with intrusion sustained AIS 2+ injury attributed to contact with intrusion (CCIS)
- High proportion of fatal and MAIS 2+ injuries in cases with high overlap (>75%)
   - In GIDAS, 41% of MAIS 2+ survived were in high overlap cases
   - In CCIS, 40% of MAIS 2+ survived and 31% of fatal occupants were in crashes with high overlap
- GIDAS analysis showed that the proportion of MAIS 2+ injuries due to acceleration loading (i.e. injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures) increased for higher overlap cases, whilst proportion of MAIS 2+ injuries due to contact with intrusion increased for lower overlap cases
   - In GIDAS 25% of MAIS 2+ survived were in low overlap cases indicating possible issues with low overlap and/or narrow object impacts. However, much lower percentages were seen in car-to-car impacts and CCIS data.
- Greater proportion of fatal and MAIS 2+ injuries for elderly occupants compared with other age groups
   - In CCIS dataset, occupants over 60 years old represent 18% of injured occupants, however account for 52% of fatalities and 25% of MAIS 2+ survived occupants
- In GIDAS, serious injuries (AIS 2+) due to acceleration loading (restraints) could be identified to occur more often for women than men and are linked with slightly higher proportions for front passengers than drivers.

10 ACKNOWLEDGEMENTS

This report used accident data from the United Kingdom Co-operative Crash Injury Study (CCIS) collected during the period 2000-2009. CCIS was managed by TRL (Transport Research Laboratory), on behalf of the DfT (Transport Technology and Standards Division) who funded the project along with Autoliv, Ford Motor Company, Nissan Motor Company and Toyota Motor Europe. Previous sponsors of CCIS have included Daimler Chrysler, LAB, Rover Group Ltd, Visteon, Volvo Car Corporation, Daewoo Motor Company Ltd and Honda R&D Europe (UK) Ltd. Data was collected by teams from the Birmingham Automotive Safety Centre of the University of Birmingham; the Transport Safety Research Centre at Loughborough University; TRL and the Vehicle & Operator Services Agency of the DfT.

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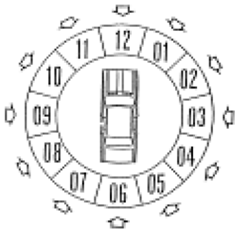
12 GLOSSARY

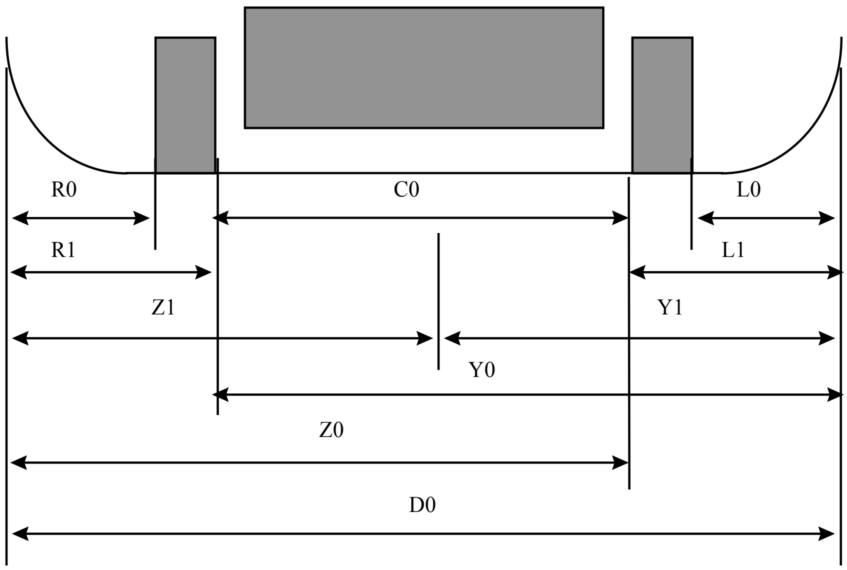
AIS:	Abbreviated Injury Severity Scale, describing the mortality rate of an injury ranging from 0 (not injured) to 6 (medical treatment today impossible), AIS 1 injuries and sometimes also AIS 2 injuries are reported to be superficial; Injuries above a certain level are often described as AIS X+ (e.g., AIS 2+ meaning injuries with severity levels 2, 3, 4, 5 and 6). In the databases AIS 9 is often coded for unknown severity level
CDC:	Collision Deformation Classification, VDI (see below) is derived from CDC
Deceleration injuries:	injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures. Deceleration injuries are sometimes referred to as 'restraint' or 'restraint related' injuries.
delta-v:	velocity change following a collision
DRV:	Driver
EES:	Energy Equivalent Speed describing the deformation energy by a velocity that would create this deformation with $E_{def} = ½ m EES^2$
ETS:	Estimated Test Speed; test speed of the vehicle against a rigid fixed barrier that would cause the same deformation. Note: similar to EES.
HGV:	Heavy Goods Vehicle / large truck (within GIDAS study also including coaches and busses
MAIS:	Maximum AIS coded, i.e. the most severe injury
Mass ratio:	relationship between the mass of two vehicles with mass ratio larger than one meaning the opponent vehicle is heavier than the case vehicle
FSP:	Front Seat Passenger
FPS:	Front Passenger Seat
PDOF:	principle direction of force, see also VDI1
PSV:	Public Service Vehicle (busses and coaches)
VDI:	Vehicle Deformation Index; is used in GIDAS in order to code the deformation of a vehicle in a seven figure code. The first two digit figure (VDI1) describes the principle direction of force, the second figure (VDI2) is a one digit code describing which part of the vehicle (front, right side, roof, …) is deformed and the third part (VDI3) describes the horizontal distribution of the deformation. The other parts are not of relevance for this study
VDI1:	The first part of the vehicle deformation index describes the principle direction of force in a clock wise system. For example 12 o'clock means

accidents with a principle direction of force between -15° and +15° from the front, see also Figure below.



VDI2: The second part of the vehicle deformation index indicates which part of the vehicle is mainly damaged (e.g., front, right side, rear, …)

VDI3: The third part of the vehicle deformation index describes the horizontal distribution of the main deformation. VDI2 is defined differently for the different zones according to VDI2. However, within the scope of FIMCAR only deformations to the car front are of interest. The different zones for the horizontal distribution are shown in the Figure below.



APPENDIX A: REPRESENTATIVENESS OF CCIS DATA SET

It is known that there are some differences in the characteristics of the GB CCIS in-depth accident data and the national accident data. These are caused by the accident sampling procedure for CCIS which is biased to fatal and serious accidents and to new cars.

The characteristics of the CCIS data set used for the compatibility analysis and an equivalent STATS19 data set were compared to quantify any biases in the CCIS data set. This was necessary to help ensure that the results of the compatibility analysis performed were interpreted correctly.

The CCIS data sample selection criteria were:

- Occupant in car or car derived van
- Car involved in 'significant' frontal impact without significant rollover
- Car registered in year 2000 onwards and ECE Regulation 94 compliant

The STATS19 data set used data from accidents which occurred in 2008 and was adjusted to represent a fleet that comprised entirely of R94 compliant vehicles using the scaling factors derived by D Richards *et al*. 2010 shown in Table A-1.

Table A-1: Adjustment to 2008 STATS19 data based on the entire fleet being compliant with ECE Regulation 94

Vehicle hit	Fatal	Serious	Slight
Adjustment to 2008 figures	98%	90%	101%

The results were:

- Little / no difference was found in the proportions of fatal and serious injured occupants in the data sets when just fatal and seriously injured occupants were considered.

Table A-2: Comparison of distribution of fatal and seriously injured occupants in STATS19 and CCIS data sets.

	Fatal	Serious
STATS19	10.2%	89.8%
CCIS	11.6%	88.4%

- A higher proportion of HGV/bus impacts and a lower proportion of narrow object impacts was seen in the CCIS data set compared to the STATS19 national accident data set.

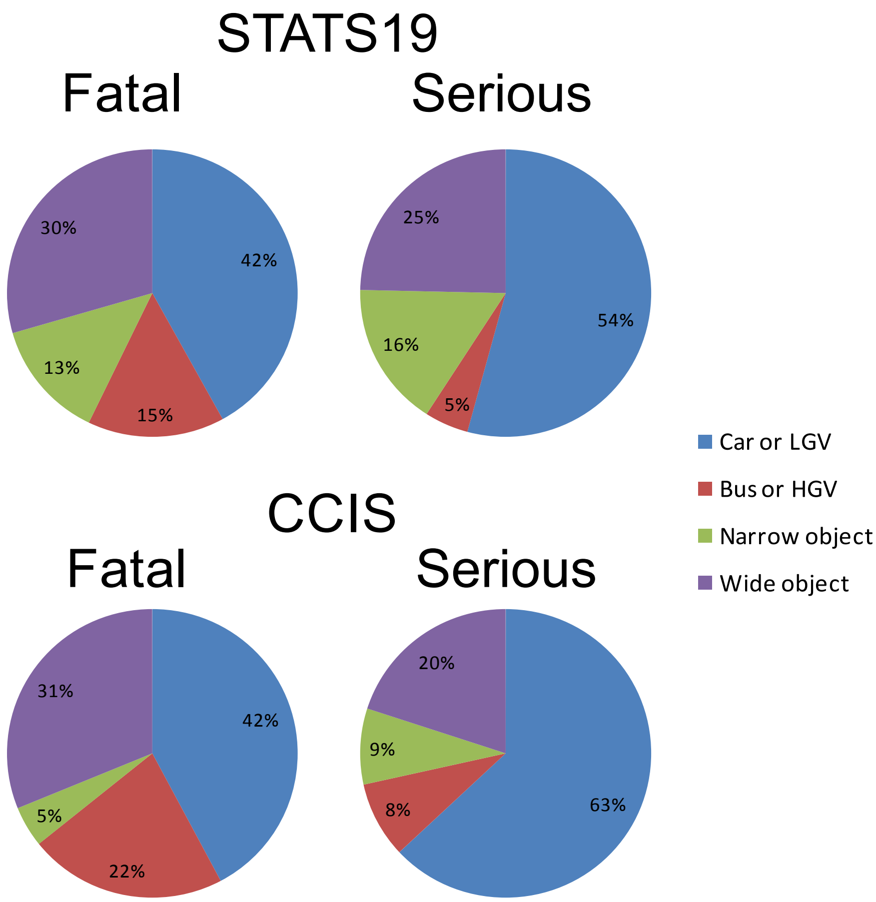


Figure A.1: Distribution of impact type for Regulation 94 compliant vehicles in STATS19 and CCIS

- A greater proportion of the occupants in CCIS are elderly (aged 66 or older), and a smaller proportion are aged 12-25 years.

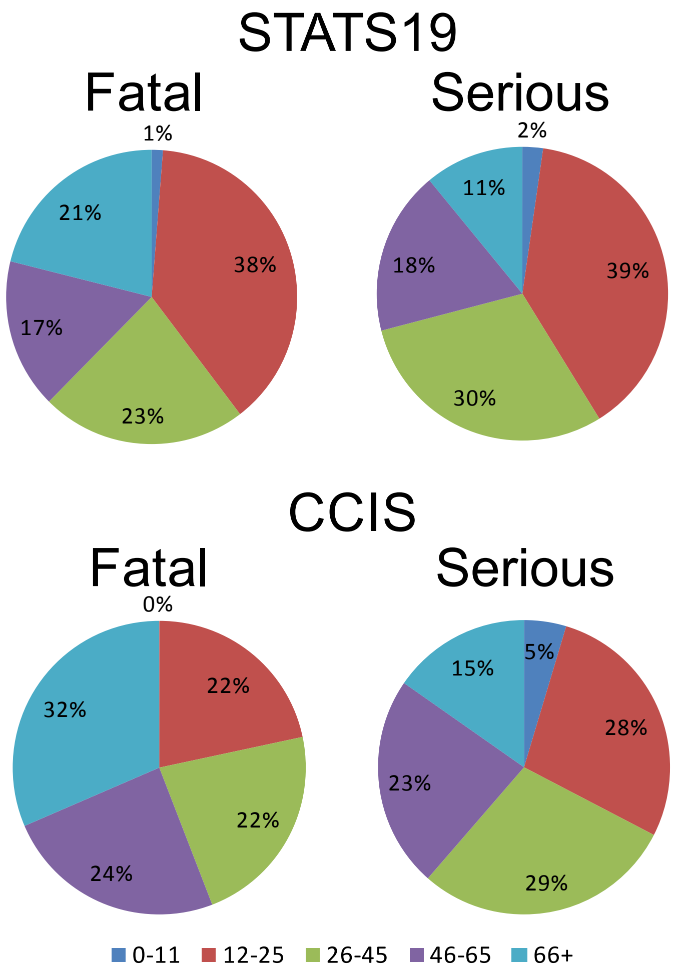


Figure A.2: Distribution of casualty age for Regulation 94 compliant vehicles in STATS19 and CCIS

In summary, it was found that the CCIS data set has a higher proportion of HGV/bus impacts, a lower proportion of narrow object impacts and a bias towards older occupants.

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FIMCAR
III – Car-to-Car Test Results

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The assessment of compatibility in frontal impacts has to address the importance of different vehicle structures. A critical component in the assessment is to identify, quantitatively, what constitutes good performing structures. In particular, the concepts of structural alignment and structural interaction need to be investigated. Structural alignment is incorporated in the FIMCAR candidate compatibility assessments to achieve geometric alignment of identifiable crashworthiness structures. Structural interaction is also a global assessment of how structures interact with a collision partner during the crash. The performance of lower vehicle structures in a crash has been identified as important as they may not be evaluated in a structural alignment assessment, but can contribute to structural interaction and thereby improve collision outcome. There has been, however, no clear definition of the characteristics for lower load paths that improve vehicle safety and how these structures manifest themselves in proposed test procedures.

FIMCAR has developed a vehicle crash test program that investigates the performance of vehicle structures using three different test series. The first test series used Super mini vehicles with different front end architectures. These tests with, and without, geometric alignment allowed the effectiveness of a lower load path to be compared to a case without a lower load path. A second set of tests investigated the importance of lower load paths for SUV type vehicles where the main front structures may not align with the main structures in a collision partner, but a lower load path may offset the consequences of this initial misalignment. A final test series investigated how the lower load paths in higher SUV type vehicles influence safety in side impact conditions and thus identify potential side effects of a new assessment procedure.

Results of the test program show that the presence of a lower load path contributes to a more robust performance of the vehicle. The rearward offset of a lower load path could be reviewed and used to quantify when a lower structure design can contribute to structural interaction in both frontal and side impact configurations.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work was accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this report is to analyse and summarise the car-to-car test program performed within the FIMCAR project.

1.3 Structure of this Deliverable

The report starts with a chapter on the background regarding frontal impact compatibility research including available car-to-car test results. In Chapter 3 the objectives of the FIMCAR test programme and the test programme itself including the results are explained. The discussion of the test results takes place in Chapter 4.

2 BACKGROUND

The development of a set of test procedures which address self and partner protection is the focus of the FIMCAR – Frontal Impact and Compatibility Assessment Research - project. The goal is to decrease the injury risks in single and multiple vehicle frontal impact accidents by developing standardised laboratory test conditions that promote more robust vehicle crash performance in the real world. It is expected that compatible vehicles will deform in a stable manner allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved. The challenge for compatibility researchers has been an assessment to identify and quantify the parameters that influence crash performance and a method that assesses them reliably and objectively.

Previous research has exploited a combination of testing and simulation to explore frontal crashworthiness and most agree that structural interaction, compartment strength, and frontal force levels are the parameters that can describe how vehicles interact with a collision partner. While these compatibility concepts are universally agreed upon, individual interpretations and assessments vary and, more importantly, the quantification of the parameters has been elusive.

One of the most comprehensive test programs addressing vehicle-to-vehicle compatibility was the VC-Compat project [Edwards 2007]. The test program comprised car-to-barrier and car-to-car tests using a range of vehicle classes. The test program was designed to evaluate car-to-car crash performance using a reference performance for the vehicle. Obtaining internal design requirements from individual manufacturers was not possible so the use of Euro NCAP test performance was used as reference. Euro NCAP is a duplicate of the current European frontal impact requirements for a car (UNECE Regulation 94) but conducted at a higher speed. EEVC Working Group 11 [Lowne 1996] designed the R94 56 km/h test condition to duplicate an impact of 2 identical cars into each other at 50 km/h (100 km/h closing speed) and 50% overlap. Although the R94 test data is proprietary, the consumer test data from Euro NCAP was available for some vehicles and its 64 km/h impact speed was considered equivalent to 56 km/h (112 km/h closing speed) and 50% overlap vehicle-to-vehicle crash test.

Another approach to vehicle-to-vehicle tests is used by NHTSA where a 100% overlap test condition is used. In contrast to Europe were compatibility research focuses on passenger car-to-passenger car impacts, NHTSA has focused on the LTV-to-passenger car impacts due to the high proportion of LTVs in both vehicle registrations and vehicle casualty crashes [Summers 2003]. The crash tests reported in [Summers 2003] were conducted at 48 km/h (96 km/h closing speed) but subsequent test approaches [Summers 2005] were modified so that a target speed change for the lighter vehicle, 56 km/h, was produced to facilitate comparison of results for different bullet vehicle masses.

FIMCAR research activities focus on the European accident and vehicle designs so the previous test approach used in VC-Compat is the framework for further test programs. This will allow the new data to be readily compared to the previous research, such as the EEVC WG15 [Faerber 2007], VC-COMPAT project [Edwards 2007], and IHRA [O'Reilly 2003].

2.1 Summary of Previous Research

As justified previously, the main starting point for FIMCAR was the VC-Compat database of vehicle test data. The car-to-car tests in VC-Compat are shown in Table 1 could be grouped into four test series which had specific goals.

Table 1: VC-Compat vehicle-to-vehicle crash tests [Edwards 2007].

	Vehicles	Organisation	Aim of test series
1.	Small Family (1 load path) Small Family (1 load path)	BASt	Series 1: Investigate difference in structural interaction performance of vehicle that spreads its load well vertically (two load path level design) with one that doesn't (single load path level design).
2.	Small Family (1 load path) Small Family (2 load path)	TNO	
3.	Small Family (2 load path) Small Family (2 load path)	UTAC	Series 2: Investigate difference in structural interaction performance of vehicle that spreads its load well vertically (two load path level design) with one that doesn't (single load path level design) *for state of the art current design cars*.
4.	Small Family (1 load path) Small Family (1 load path)	FIAT	
5.	Small Family (1 load path) Small Family (2 load path)	TRL	
6.	Supermini Supermini	FIAT	Series 3: Investigate difference in performance of light vehicle when impacted by cars with different structural interaction potential (single and two level load path vehicles used in test series 2).
7.	Supermini Small Family (2 load path)	UTAC	
8.	Supermini Small Family (1 load path)	BASt	
9.	SUV (no SEAS) Small Family (2 load path)	BASt	Series 4: Investigate difference in performance of car in impact with SUV if it has an additional load path not necessarily in alignment with the SUV vehicle structure (single and two level load path cars used in test series 2). Investigate if the performance of the car is improved if the SUV has a secondary energy absorbing structure (SEAS).
10.	SUV (SEAS) Small Family (2 load path)	TRL	
11.	SUV (no SEAS) Small Family (1 load path)	VW*	
12.	SUV (SEAS) Small Family (1 load path)	BASt ADAC*	

*Tests performed outside of the VC-Compat project to which the group have access to the results
Detailed test reports can be found in the appendices of D27 (D17 report appendices for tests 1 and 2)

Some of the main findings of these tests were:

Series 1: The test vehicle used had poor compartment strength and exhibited unstable performance against itself or another partner vehicle. This finding was similar to results in [Summers 2003] when the weak compartment of a target vehicle produced significant intrusions to the occupant compartment, regardless of the bullet vehicle configuration.

Series 2: A multiple load path vehicle exhibited better performance than a single load path vehicle when striking itself or the single load path vehicle. Performance was based on the Euro NCAP performance baseline.

Series 3: The mid-size vehicles in Test Series 2 exhibited similar performance when impacting a smaller target vehicle. The test series confirmed the benefit of vertical load spreading and compartment strength but did not confirm the benefit of the multiple-load path vehicle

Series 4: Large SUVs impacted the mid-sized vehicles in Series 2 with mixed results. The SUV without a lower load path was not as aggressive when striking the single load path SFC from Series 2 and a similar situation was found for the SUV with a lower load path and the multiple load path SFC. There was no clear evidence that one SUV design was better than the other.

The test vehicles used in VC-Compat were designs that could be considered as transitional vehicles during the implementation of R94 which became mandatory in 2003. The vehicles exhibited combinations of different compatibility characteristics which were not consistently good or bad. For example, the small family and SUV vehicles with lower load paths also had weak bumper cross beams while the single load path vehicles had much stronger cross beams. This made any analysis of car-to-car tests difficult as the crashworthiness designs could not be systematically assessed in all configurations due varying deformation modes. General conclusions on benefits for different architectures could be identified but it was not possible to develop evidence that mandated, for example, lower load paths on cars or strong cross beams.

Given the 6 years between the VC-Compat and FIMCAR start dates, as well as new accident data available, it was important for FIMCAR to re-evaluate the performance of recent vehicle designs that could be better correlated to the accident data analysed in FIMCAR Deliverable D.1.1 [Thompson 2013] and Section II, and additional accident analyses [Pastor 2009/1, Pastor 2009/2]. Based on these accident data FIMCAR members have set priorities for the development of the test procedures and metrics.

In order to address compatibility, a list of compatibility characteristics was identified and prioritized within the consortium, see Table 2. The description of the development of the list was described in [Thomson 2012] and Section XIII. The top priorities with respect to this report are that the test procedures should address structural interaction, restraint performance and maintenance of current levels of compartment integrity.

Table 2: Main compatibility topics and associated priorities.

	Assessment requirements							
	Structural Interaction		**Front End Force / Deformation (Consisting of)**		**Compartment integrity**		**Restraint system**	
	Alignment	Load Spreading (Load paths / connections)	Deformation forces of frontal structures	Energy Absorption Management	Sufficient for single vehicle accident	Enhanced for light vehicles in vehicle to vehicle accident	(Assess over range of pulses)	Test Restraint Capacity
Priorities For FIMCAR	1	1	2	1	1	2	1	1

The importance of structural interaction could be shown in FIMCAR accident analyses and in previous studies [Edwards 2007]. There were lower priorities on the deformation force which means that frontal force mismatching was not identified in FIMCAR as had been expected from earlier studies [Faerber 2007]. The compartment integrity is in most cases sufficient but should not be lowered, however, it is not clear if this is due to the UNECE Regulation 94 requirement or due to the higher requirements from Euro NCAP. There was no clear evidence that this was a particular issue with smaller vehicles. However, special attention should be put on acceleration induced injuries which should be assessed with tests introducing a range of pulses.

3 CAR-TO-CAR TESTING

3.1 Test Programme

Three different test series consisting of eight car-to-car crashes were conducted within the FIMCAR project. Table 3 shows a summary of the test program. Each test series had specific questions that were to be answered by the test results and support the compatibility metrics being developed in parallel activities in FIMCAR.

Note: The third test in Test Series 2 was not performed according the test specification (the original plan was to modify the ride height of the cars in order to achieve misaligned conditions; unfortunately the ride height was not adopted). Due to this mistake, the test did not help to answer all questions that were expected. Following that, the analysis of this test is treated separately at the end of Chapter 3.3.

Table 3: FIMCAR car-to-car test program.

Test Series	Vehicle	Aim of the test	Test setup
1	Supermini 1 (PEAS) Supermini 2 (PEAS & SEAS)	The effect of structural alignment in vehicle equipped with lower load path compared to a case without a lower load path	Frontal car-car 56 km/h 50% offset
2	Small family car 1 (PEAS & SEAS) SUV 1 (PEAS & SEAS) SUV 2 (PEAS)* * test condition different from original plan	The effect of structural alignment and lower load path in SUV type vehicles crashing against a small family car	Frontal car-car 56 km/h 50% offset
3	Large family car 1 SUV 3 (PEAS & SEAS)	Investigate the importance of lower load paths for SUV type vehicles in side impact crash	Side impact car-car 50 km/h

3.2 Test Series 1 – Supermini vs. Supermini

Two different vehicle models with different front end architectures where tested, Supermini 1 (named SM1) equipped with PEAS only, and Supermini 2 (named SM2) with both PEAS and a SEAS in line with the bumper. The vehicles were tested both with aligned and misaligned front structures (see Figure 3.1). The test speed was 56 km/h with a 50% overlap and 50th percentile Hybrid III dummies were positioned in the front seats according UN-ECE Regulation 94 procedure.

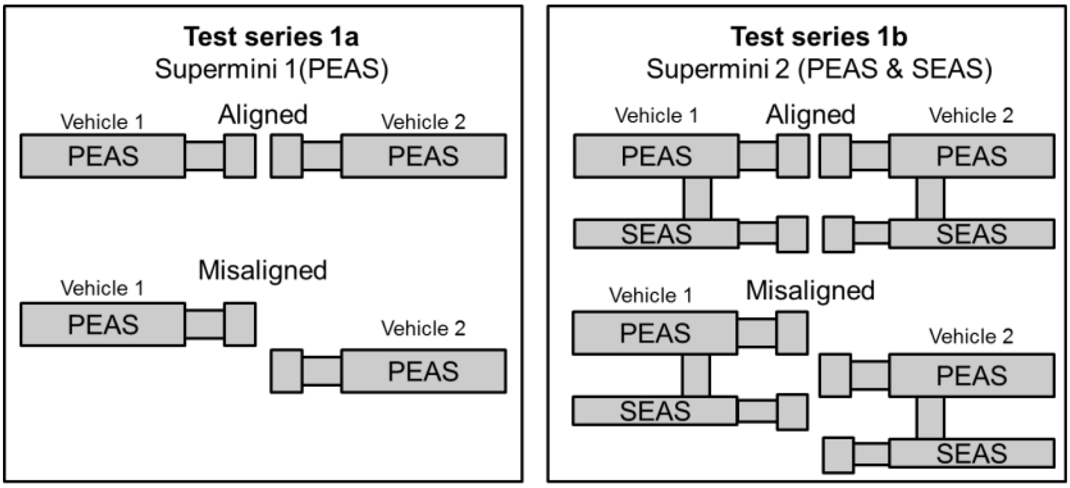


Figure 3.1: Test configurations in Test Series 1.

3.2.1 Results Test Series 1– Acceleration

The most obvious difference between the car model with both SEAS and PEAS (SM2) compared to the car with only PEAS (SM1) is a more rapid build-up of the acceleration in the initial stages of the impact (Figure 3.2). Comparing the mean acceleration for the first 300 mm of stopping distance, the SM2 has more than twice the acceleration of SM1. Both vehicles have a reduced acceleration build-up in the load case with misaligned front structures, but the reduction is greater in the car without SEAS (SM1). Comparing the acceleration to the case when the cars were tested in the Euro NCAP, both cars have higher average acceleration in the first 300 mm in car-to-car tests than in Euro NCAP when tested with aligned front structures. The car without SEAS (SM1) has lower acceleration than Euro NCAP in the misaligned test, while SM2 still has higher acceleration than Euro NCAP even in the misaligned test. The SM2 vehicle also has the highest peak acceleration. Regardless if the structures are aligned or misaligned, the peak acceleration is higher than in the Euro NCAP test. The car with only SEAS (SM1) has roughly the same max acceleration as in Euro NCAP test conditions.

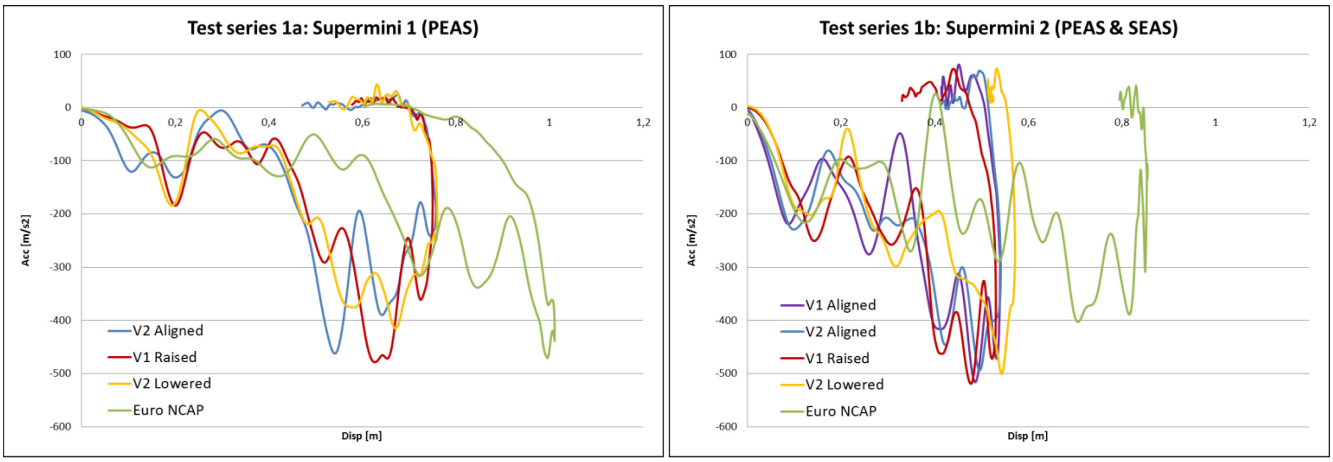


Figure 3.2: Acceleration measurement Test Series 1 (measured on left B-pillar root).

3.2.2 Results Test Series 1 – Intrusions

The car with only PEAS (SM1) has higher intrusions than the car with both PEAS and SEAS (SM2) as seen in the left side of Figure 3.3. The difference is greater when tested with misaligned front structures. Notable is that both cars have a higher A-pillar intrusion compared to the Euro NCAP test, even in the load case with front structures aligned. There is a slight case of over/under ride problems when the vehicles are aligned, which is more pronounced in the misaligned load case. It is always the overridden vehicle that has the highest A-pillar intrusion.

The intrusions in SM2 are shown in the right graph of Figure 3.3. This vehicle obviously has a stronger passenger compartment and front end design as seen in both Euro NCAP and aligned car-to-car test intrusions. It is important to note that the vertical misalignment of SM2 was about 100 mm while it was only 75 mm for SM1. The intrusions in SM2 were consistently lower than SM1 in the misaligned load case and demonstrate the role of multiple load paths when structures are not in complete alignment.

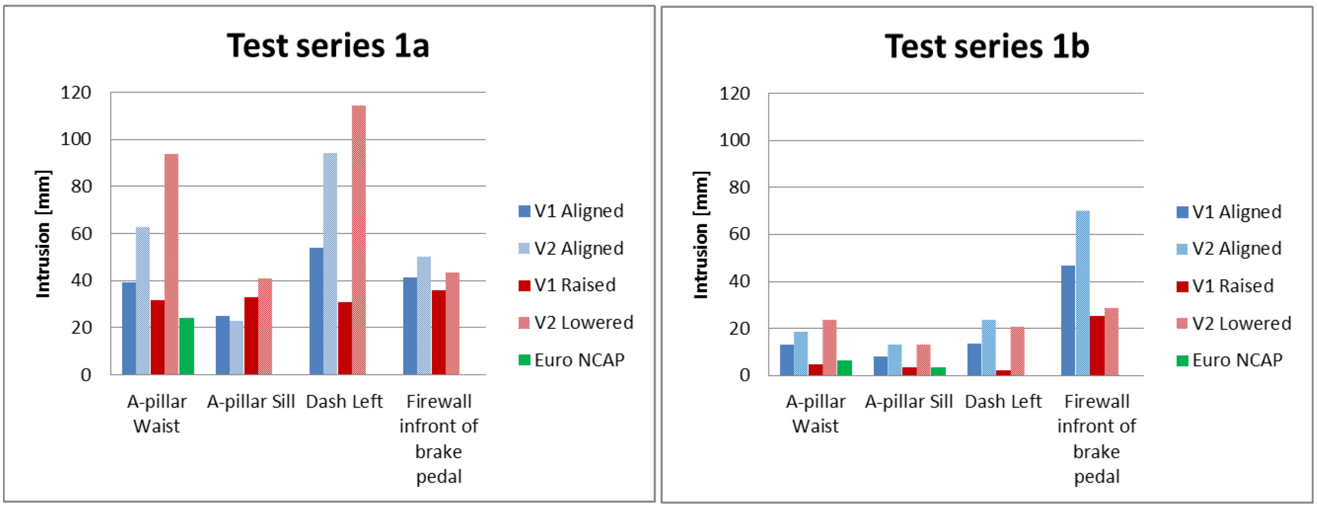


Figure 3.3 : Intrusion measurement test series 1 (left side SM1 and right side SM2).

3.2.3 Results Test Series 1 – Dummy Criteria

The dummy criteria for the driver are shown in Figure 3.4 as a percentage of the ECE Regulation 94 limits. There is no obvious trend between the vehicles and the different load cases. Notable is that both vehicles have dummy criteria that in many cases are higher than in the Euro NCAP test. It could also be seen that SM2 in the aligned load case has two values on or above the ECE Regulation 94 limits (Head Res Acc and HIC36). The passenger seat inner rail lock failed in Vehicle 2 causing the passenger dummy to interfere with the driver dummy. The driver dummy in Vehicle 2 did not contact the airbag was not centered as in Vehicle 1 and this may have contributed to the higher head accelerations.

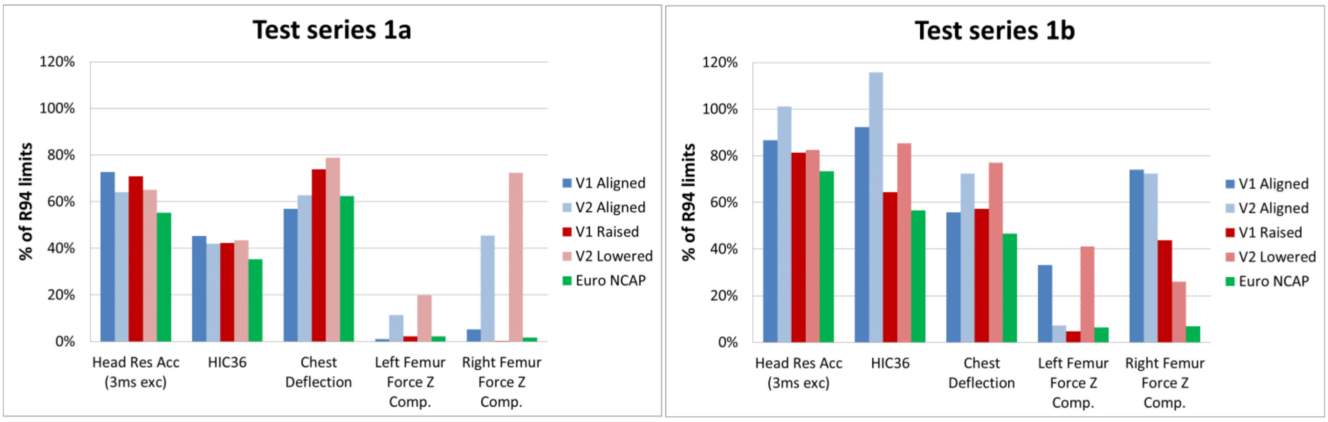


Figure 3.4 : Dummy criteria Test Series 1 as percentage of ECE-R94 limits.

3.3 Test Series 2 – SUV vs. Small Family Car

Two different vehicle types were tested. One SUV (named SUV1) equipped with PEAS and SEAS striking a target small family car (named SFC1) also equipped with PEAS and SEAS. Both vehicles have a SEAS located 100-200mm behind the bumper beam. Two tests were performed, one with misaligned front structures (normal ride heights) and one with the front structures aligned (see Figure 3.5). The test speed was 56 km/h with a 50% overlap and 50th percentile Hybrid III dummy where positioned in the driver seat according to UN-ECE Regulation 94 procedure, and a 5th percentile female dummy in the passenger seat. This test was designed to investigate the issues related to SUVs which are typically designed with high PEAS and need to keep the area in front of the wheels as clear as possible to provide adequate approach angles in off road conditions. There was an open question as to how the SEAS will function in a car-to-car test and how it will be detected in a barrier impact. Figure 3.5 shows the test setup for Test Series 2.

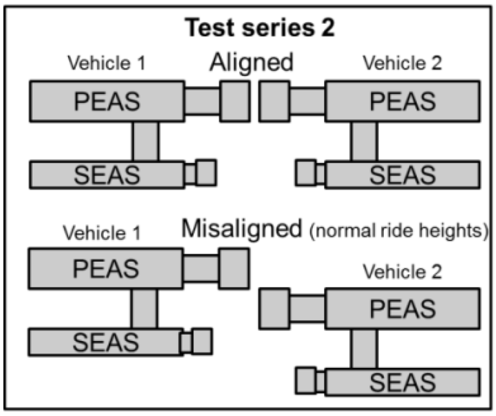


Figure 3.5: Test configurations Test Series 2.

3.3.1 Results Test Series 2 – Acceleration

Figure 3.6 shows the accelerations measured at the B-pillar root on the impact side of the vehicles. The acceleration measurement failed for the SUV1 in the misaligned load case, thus no comparison to the aligned load case is possible. The acceleration data for SFC1 is summarised in Figure 3.6. In the load case with aligned front structures SFC1 has higher mean acceleration the first part of the crash (first 300 mm of deformation) and lower peak acceleration. The delta-v is reduced to a level comparable to what the car has in the Euro NCAP test.

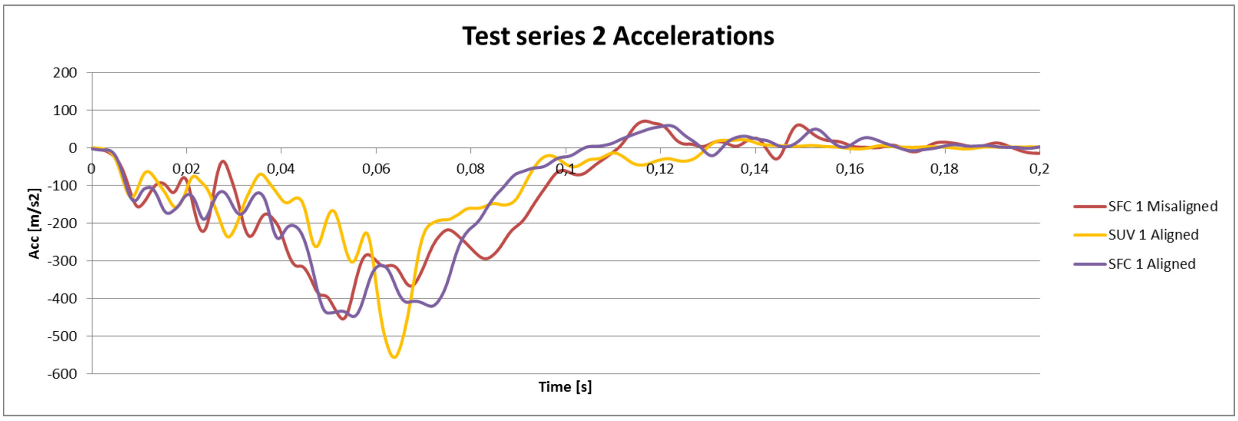


Figure 3.6: Accelerations Test Series 2.

Table 4: Acceleration data small family car Test Series 2.

	Small family car Aligned	Small family car Misaligned	Small family car EU-NCAP
Max displacement [mm]	732	739	1243
Max deceleration [m/s$^{2]}$	447	454	392
Mean decaleration 0-300mm [m/s2]	94	80	No data
DeltaV [km/h]	75,5	78,9	75,6

3.3.2 Results Test Series 2 – Intrusion

Figure 3.7 shows the intrusion measurements. As expected, the smaller car has, in general, higher intrusions than the SUV. The overriding situation of the SFC in the non-aligned test compared to the aligned one results in higher intrusions in the upper area of the cabin (dashboard) but reduced intrusions in the lower part (firewall left floor rest). For the SUV the intrusions are low and with no obvious trend, it is only the measurement at left footrest that stands out. No obvious reason for the intrusions at the footrest has been found.

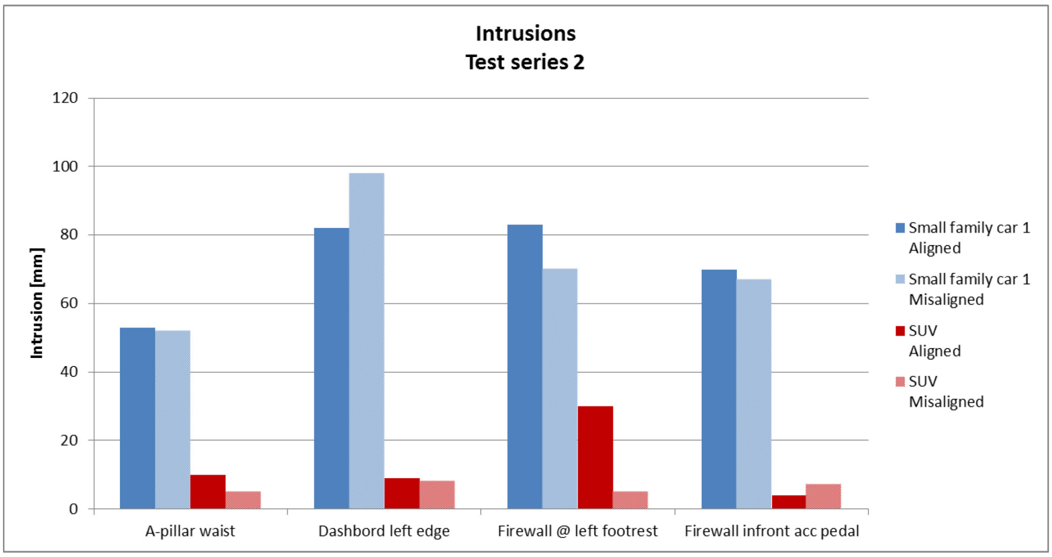


Figure 3.7: Intrusion measurement Test Series 2.

3.3.3 Results Test Series 2 – Dummy Criteria

The dummy criteria are shown in Figure 3.8 as percentages of the ECE Regulation 94 limits. The measurements show no clear trend, but for the SFC, 3 of 4 values (chest deflection, femur compression and tibia index) show an improvement in the load case with aligned frontal structures compared to the non-aligned situation, and for the SUV 3 of 4 values shows deterioration when the cars have their front structures aligned.

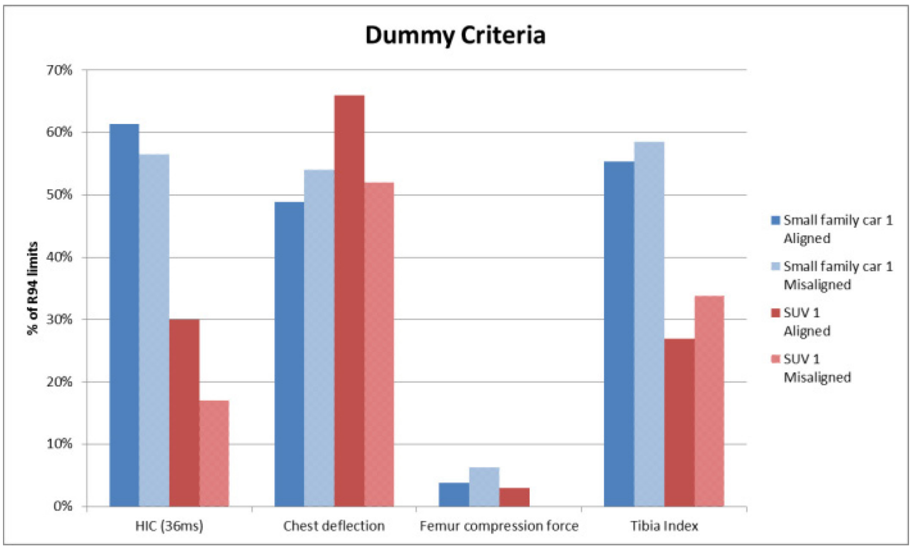


Figure 3.8: Driver dummy criteria Test Series 2.

3.3.4 Additional Test in Test Series 2

Test Series 2 was planned to consist of 3 different tests. The third test was planned to be a production SUV (SUV2) without SEAS in a misaligned test with the Small family car (SFC1). The purpose of that test was to compare the results with those from the first test in the series with an SUV with both PEAS and SEAS in the misaligned load case. This test case would allow for further study of the effect of a lower load path. By mistake this test was performed with wrong ride height on the SUV2 with the result that the vehicles where crashed with the PEAS of both vehicles being almost aligned. Therefore it is impossible to quantify the disbenefit from high PEAS cars without appropriate SEAS. However, literature is proving poor behaviour [Patel 2009].

Despite the incorrect test condition, some interesting observations that highlight the complexity of compatibility are worth discussing. The vehicles were vertically aligned according to Figure 3.9. The cross member of the SUV2 overlaps 96% of the SFC1 cross member, and the SFC1 cross member overlaps 64% of the SUV2 cross member. Despite this (initially) relatively high vertical overlap, the PEAS of the SUV2 was able to locally deform the crossbeam of the SFC1 and impacted the SFC1 gearbox. This “fork-effect” phenomenon could potentially be avoided with a horizontal load spreading requirement, which would require stiffer cross members that could decrease the risk for cross members to deform between the PEAS despite being initially aligned.

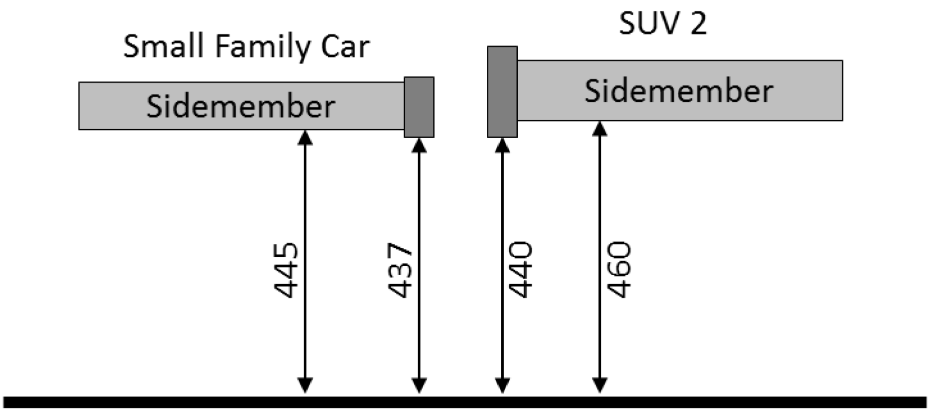


Figure 3.9: PEAS vertical alignment.

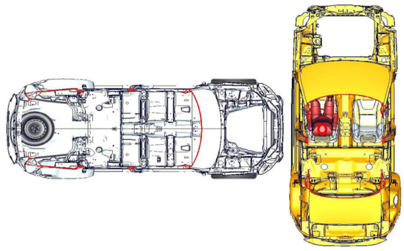
Due to the longitudinal side member of SUV2 impacting the gearbox of SFC1, the gearbox broke while the SUV2 side member remained undeformed. The intrusions in the SFC1 compartment were kept relatively low. The fact that the gearbox of the SFC1 broke could have helped reducing the intrusions, because it is likely that if the gearbox would have remained intact, it would instead have been pushed more rearward in to the compartment area of the SFC1. One other event that worked in favour of the SFC1 was that its longitudinal side member did impact the wheel of the SUV2. This created a load path from the sill of the SUV2 via the wheel into the longitudinal side member of the SFC1, allowing the side member to deform and absorb energy (as it is designed to do). If the SFC1 side member would not have impacted the wheel in such a favourable way (e.g., in an accident with a slightly different off-set), it is likely that the results for the SFC1 would have been much worse. So in summary, one can say that different combinations of local contacts between the crash partners have quite an impact on the result for the smaller car in this test. This highlights the complexity of compatibility, particularly structural interaction, in car-to-car collisions.

3.4 Test Series 3 - SUV vs. Large Family Car

In test series 3, an SUV (named SUV3) originally equipped with a SEAS longitudinally in line with the bumper beam, crashed into the side of a large family car (named LFC1). The SUV3 (bullet vehicle) was travelling at 50 km/h and a 90° angle into LFC1 (target vehicle). The bullet's longitudinal centre line was in line with the COG of the drivers head in the target vehicle. Two tests were performed, one reference test with SEAS and one test with the SEAS removed. The test setup can be seen in Table 5 and the pre-crash alignment in Figure 3.10.

Table 5: Test Series 3.

<table>
<tr><td rowspan="2">Test Date
1;st test
2;nd test
Location
Topic
Mass Ratio
Test Number
1;st test
2;nd test
Test Protocol</td><td rowspan="2">
Febr. 15, 2012
Febr. 29, 2012
VCSC
Car to Car
1:1.1

122129
122130
Car-to-car test</td><td colspan="4">SUV 2
50 km/h

LFC 1
0 km/h</td></tr>
<tr><td>Vehicle 1:
Type:
Impact side:
Speed:
Overlap:
Test mass:
Dummy:</td><td>SUV
SUV
Front
50 km/h
100 %
1935 kg
LHS – H III 50%</td><td>Vehicle 2:
Type:
Impact side:
Speed:
Details:
Test mass:
Dummy:</td><td>Sedan
Large family car
Left side
0 km/h
-
1761
LHS F – ES2</td></tr>
</table>

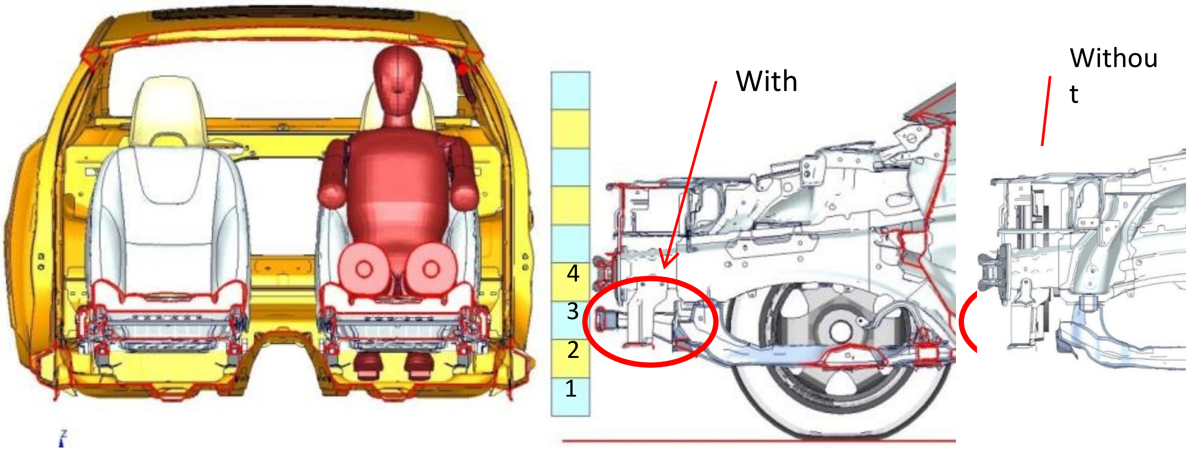


Figure 3.10: Pre-crash alignment compared to load cell wall.

3.4.1 Results Test Series 3 – Structure

The reference vehicle with the lower load path put a higher load on the B-pillar resulting in higher B-pillar velocity and intrusion (measured at the dummy chest location) compared to the modified test without lower load path. This can be seen in Figure 3.11.

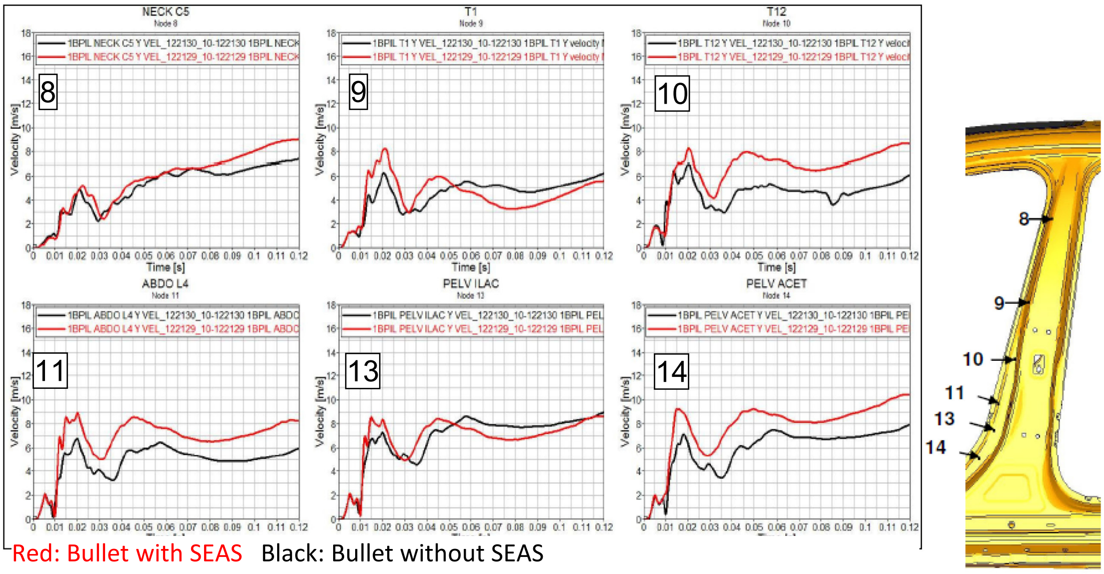
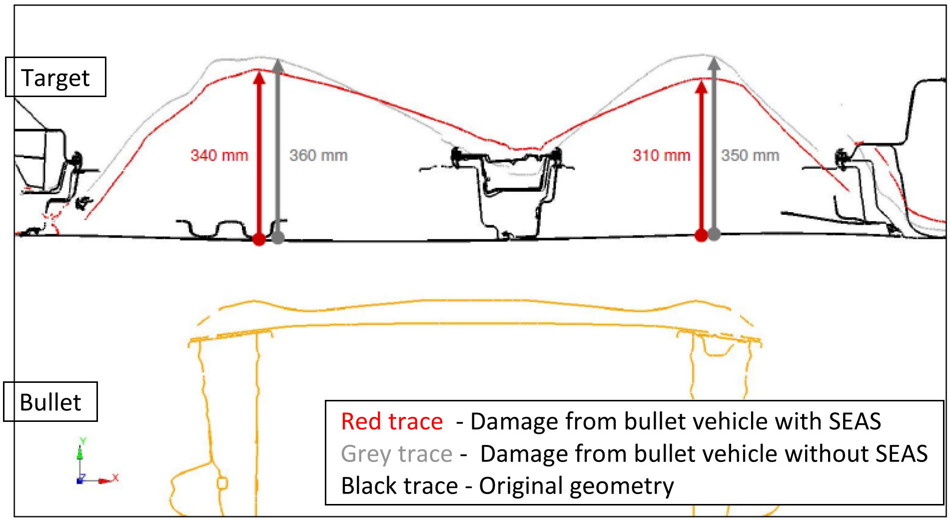
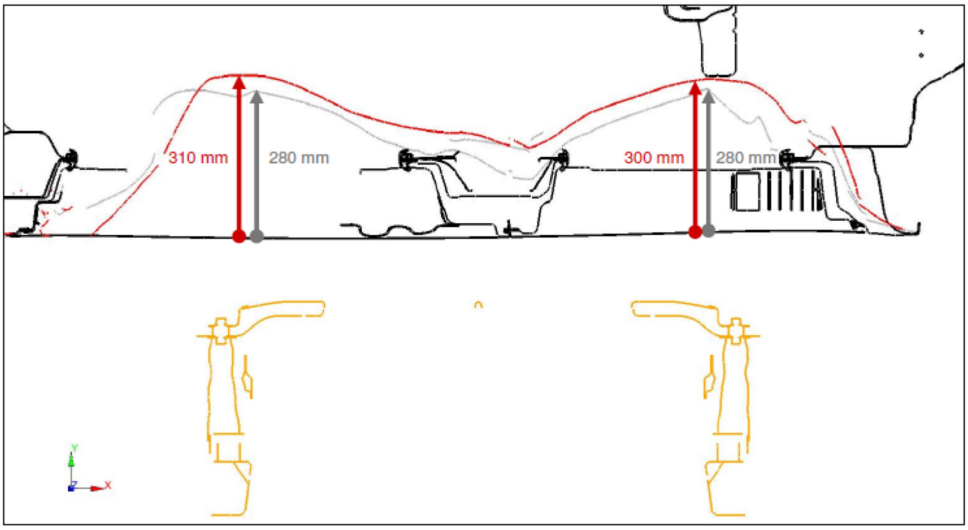


Figure 3.11: B-pillar velocities at different locations.

This behaviour arises when the lower load path on the bullet vehicle hits the B-pillar above the sill. The sills on most passenger cars are located at a height of 200-300 mm. Compared to a load cell wall this represents Row 2, while the lower load path of SUV 2 is located in Row 3 (Figure 3.10) [Adolph 2012]. The deformation of the struck vehicle is shown in the scanning measurements shown in Figure 3.12. The figures are a plan view of a scan section at two different vertical levels. The bullet without a subframe produced increased deformations of the target at the height of the bumper, also the location likely to make contact with the occupant (see Figure 3.10). Conversely, the bullet with a subframe produced more intrusion in the target at subframe level although this deformation is in a less critical area than at bumper level.



a – Scan at Level of Striking Vehicle Bumper



b) Scan at Level of Striking vehicle Subframe

Figure 3.12: Pre scan of target vehicle deformations (measurements are approximate).

The modified bullet (no forward SEAS) had a higher deformation at the centre of the bumper cross beam (see Figure) than the standard vehicle (with forward SEAS). This resulted in a 40 mm lower deformation of the target B-pillar at the point where the crossbeam contacts the target as compared to the test with the original structure. The deformation of the crossbeam resulted in a change of loading to the target, shedding loads from the target B-pillar to the surrounding door structure. The longitudinal side members in the modified SUV3 began to penetrate the doors and the left longitudinal side member began to load the dummy's femur, introducing a bending moment that was higher than for the standard bullet vehicle. The dummy values would have been higher if the impact location on the target vehicle was shifted rearward, so the longitudinal side member would directly load the dummy (due to door intrusions) or the B-pillar.

Figure 3.13: Deformation of bumper beam in modified SUV.

3.4.2 Results Test Series 3 – Dummy Criteria

For the SUV bullet vehicle, both tests showed a better result compared to the Euro NCAP test. The test speed of 50 km/h, lower than Euro NCAP frontal impact, and 10% lower mass on the target, produced lower crash loads on the bullet vehicle.

The large family car target vehicles driver dummies, in both tests, had higher values than in the Euro NCAP side collision. The bullet vehicles had higher weights, 1935 kg compared to the Euro NCAP MDB's weight of 950 kg resulting in a higher impact energy. The dummy in the reference vehicle recorded higher criteria in the chest and abdomen as a result of higher B-pillar intrusion (shown previously).

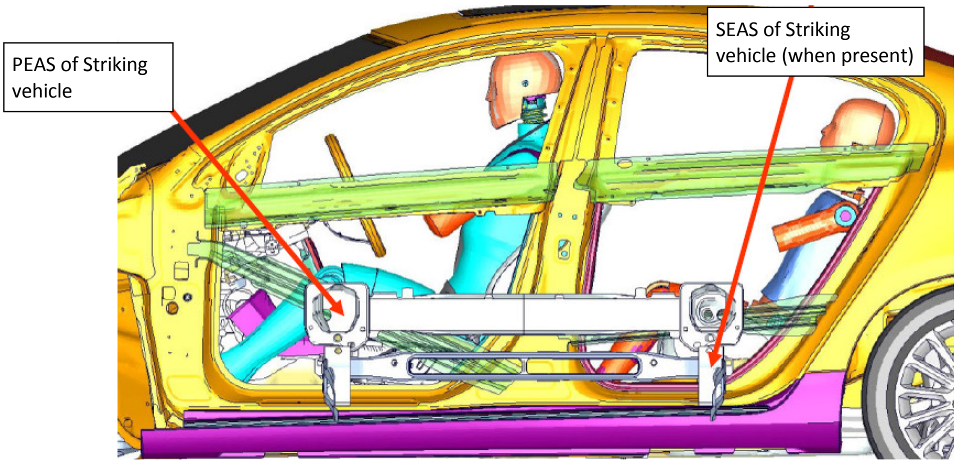


Figure 3.14: Deformation of bumper beam in modified SUV

A summary of the dummy injury values for the front and rear near side dummies is presented in Table 3.6. The results are counter-intuitive when first reviewed. In general, the vehicle struck with a vehicle equipped with a lower load path had less intrusion than when stuck with the same vehicle without the lower load path. As pointed out in the previous section, the wider distribution of the deformation caused higher B-Pillar velocities when struck with SEAS equipped vehicles. This was reflected in higher injury risks for the chest and abdomen. The influence of localised deformation can be observed in the rear seat passenger lower extremities. The lower chest, pelvis, and lateral-medial moments in the legs showed that the rear seat passenger was affected by the more focused deformation of the door when a non-SEAS equipped vehicle was the bullet. A simulation parameter study showed that the dummy injury readings were worse if the striking vehicle was shifter rearward placing the longitudinals of the bullet vehicle closer to the occupants.

The test results in Table 3.6 are not consistent with the expectations that a SEAS equipped vehicle will have improved partner protection, compared to a non-SEAS equipped vehicle, in a side impact. The target vehicle exhibited good self-protection in all cases and may have not been as sensitive to the bullet vehicle's geometry. Further testing should be conducted to confirm the simulation studies.

Table 3.6: Occupant injury assessment in struck vehicle.

Loaded by	Euro NCAP MDB	Bullet Vehicle with SEAS	Bullet Vehicle without SEAS
Position	Driver	Driver	Driver
Dummy	ES2	ES2	ES2
Head			
Peak resultant acceleration - g	20.6	32.03	25.13
Resultant Acc. 3 ms - g	19.93	30.42	23.56
HIC 15	26	99	62
Chest Top			
Compresson - mm	10.61	29.61	21.22
Viscous Criterion - m/s	0.04	0.47	0.24
Chest Mid			
Compresson - mm	8.95	27.89	17.13
Viscous Criterion - m/s	0.03	0.36	0.15
Chest Bottom			
Compresson - mm	10.17	28.45	17.67
Viscous Criterion - m/s	0.05	0.33	0.14
Abdomen			
Peak Lateral Force - kN			
Front	0.1	0.32	0.16
Mid	0.19	0.45	0.29
Rear	0.21	0.47	0.29
Total	0.44	1.24	0.75
Pelvis			
Pubic Symphysis Force - kN	1.24	2.72	1.89

Loaded by	Bullet Vehicle with SEAS	Bullet Vehicle without SEAS
Position	Rear Left	Rear Left
Dummy	Sid2S	Sid2S
Head		
Peak resultant acceleration - g	56.79	67.49
Resultant Acc. 3 ms - g	54.93	66.46
HIC 15	278	418
Chest Top		
Compresson - mm	36.4	33.3
Viscous Criterion - m/s	0.386	0.424
Chest Mid		
Compresson - mm	31.41	28.73
Viscous Criterion - m/s	0.301	0.413
Chest Bottom		
Compresson - mm	25.57	29.56
Viscous Criterion - m/s	0.25	0.336
Abdomen		
Upper: Abd. Rib Defl. - mm	24.76	28.98
Upper: Abd. Rib VC - m/s	0.221	0.416
Lower: Abd. Rib Defl. - mm	24.29	25.63
Lower: Abd. Rib VC - m/s	0.26	0.378
Pelvis		
Pubic Symphysis Force - kN	1.24	1.34
Femur		
A-P Moment (3ms) - Nm	44.71	37.32
L-M Moment (3 ms) - Nm	151.2	199.3
Resultant Moment - Nm	310.6	287.5
A-P Force (3 ms) - kN	0.601	0.343
L-M Force (3 ms - kN	0.849	1.13
Axial Force (3 ms) - kN	1.08	0.73

4 DISCUSSION

All the vehicles tested in the FIMCAR project are examples of vehicles designed to the existing legislation and consumer tests in Europe. These vehicles therefore did not have structures or occupant restraint systems designed to the anticipated FIMCAR compatibility requirements. It is important to consider that the dummy measurements reported in this study would not be expected once vehicles are designed to the anticipated requirements from FIMCAR.

The findings from Test Series 1 show that the vehicle with multiple load paths has a clearly more rapid acceleration build-up than the single load path vehicle in both aligned and misaligned cases. This is important for both restraint system trigging and the function of the restraint systems. The vehicle with both PEAS & SEAS has in general lower intrusions, and is less sensitive for misalignment regarding intrusion on A-pillar and dash. This early engagement in the crash indicates better energy absorption and a more effective use of the deformation zone of the vehicle.

Test Series 1 also showed the importance of controlling the stiffness of frontal structures for self protection reasons as expected from the introduction of a full-width test. Supermini 2 had extremely high accelerations in car-to-car collisions and this was also the case in FWDB tests. This confirms the need to control energy absorption and acceleration induced injuries with a full width test. Both vehicles in Test Series 1 were not originally designed for the North American market and it would be expected that these models would have exhibited lower accelerations in all test conditions if they had been more focus on full width test performance. The addition of a full with the test procedure would also require the restraint systems to handle a wider variety of crash pulses, which should give a better field performance.

Test Series 2 shows that structural alignment increases the mean acceleration initially and reduces the peak acceleration and delta-v for the smaller vehicle facing a heavier opponent in a frontal crash. But the improvements for the smaller vehicle can come to the cost of impairments for the heavier vehicle such as higher delta-v leading to higher acceleration generated dummy criteria. It is important to note that the SFC had no significant change in the accelerations (Figure 3.6) when impacting the aligned or misaligned SUV1. Both vertical positions of the SUV1 resulted in a positive FWDB result indicating that the FWDB test and assessment procedures could confirm that SUV1 would perform satisfactorily in frontal car-to-car crashes. Unfortunately the third test of this test series with the plan of using a single load path SUV in misaligned conditions was not performed as intended. Therefore it is impossible to quantify the disbenefit from high PEAS cars without appropriate SEAS. However, literature is proving poor behaviour [Patel 2009].

Test Series 3 shows the importance of SEAS for distributing the deformation in a side impact. Without SEAS, the longitudinals can produce local deformations that can be hazardous to the struck vehicle occupants. The larger contact area created by the distribution of forces over both Rows 3 and 4, as well as the presence of a subframe in Row 2, albeit further back, resulted in a better door intrusion profile for the occupant. Even though the dummy showed slightly better readings when struck by the modified (non-SEAS) vehicle, global performance of the original bullet vehicle indicates a better safety level. This was confirmed with a complementary simulation activity where different characteristics of the bullet vehicle were modified. The worst results for the struck vehicle were encountered when the modified vehicle had a stiff bumper crossbeam which focused its loads on Row 4 on the FWDB. The sill on most passenger cars are located at a height of 200-300 mm. Compared to a load cell barrier this represents Row 2 [Adolph 2012] (see Figure 3.10).

5 CONCLUSIONS

The results of the 3 test series demonstrate a common benefit for multiple load path vehicles, independent of the collision type. Multiple load paths exhibited a much more stable response in frontal impacts and could tolerate larger variations in structural misalignment than a single load path vehicle before serious degradation in performance were observed. Multiple load paths in SUVS were shown to be beneficial for collision partners with these higher vehicles. The SEAS tested and simulated in this test program were able to effectively engage the partner vehicle’s front structures. As both of the SUV vehicles exhibited good FWDB results (assessment criteria is described in [Adolph 2012] and Section X) and car-to-car test results, there is further confirmation that the FWDB and associated metric is able to detect good structural alignment and promote car-to-car crash safety. In addition, no significant detrimental effects (in terms of acceleration and intrusions) were observed when SUV and SFC structures were aligned.

The side impact tests provided useful input to the metric developments as well as identifying the importance of evaluating frontal impact compatibility characteristics. Even though the safety level in the struck vehicle was good in the 2 different test configurations, the different deformation profiles of the bullet vehicle demonstrated that concentrating loads on a limited number of load paths will introduce higher, local, intrusions in the struck vehicle with negative consequences for the occupants, as observed of the rear seat passenger. The fact that better target deformation was demonstrated with a bullet vehicle that spreads load vertically over Rows 3 and 4 instead of just Row 4 highlights the need for structural alignment in Rows 3&4 as well as vertical load spreading.

6 GLOSSARY

Head Res Acc	Head resultant acceleration over 3 ms (a_{3ms})
HIC	Head Injury Criterion (time weighted head acceleration metric)
HIC36	HIC analysed over a maximum period of 36 ms
LFC	Large Family Car
LTV	Light Truck Vehicle
MDB	Movable Deformable Barrier
PEAS	Primary Energy Absorbing Structures (main rails)
SEAS	Secondary Energy Absorbing Structures (lower load path)
SFC	Small Family Car
SM	Super Mini
SUV	Sports Utility Vehicle

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FIMCAR
IV – FIMCAR Models

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The aim of the FIMCAR project is to develop and validate a frontal impact assessment approach that considers self and partner protection. In order to assess the influence of different test procedures and metrics on car-to-car compatibility a huge simulation programme was executed. However, car-to-car simulations with models of different car manufacturers are almost impossible to obtain because of confidentiality.

In order to overcome these problems, parametric car models (PCM) were built, allowing fast modifications and more detailed generic car models (GCM) were developed for structural interaction analysis.

Three different PCM representing a super mini, a large family car and an executive car were developed. By simplifying the models, computational efforts are reduced. Due to the parametric design it is possible to modify the models in an easy and fast way. The models are delivered in three crash codes (LS-DYNA, PAM-CRASH and RADIOSS) in order to be usable at all FIMCAR OEMs.

The Generic Car Models (GCM) model virtual cars which represent an average real car of the respective category (super mini, small family car, executive car) in a comparable way to the OEM models. All together five different models were generated (2 super minis, 2 small family cars and one executive), again delivered in three different FE codes (LS-DYNA, PAM-CRASH and RADIOSS). The models can be used to evaluate the behaviour of the crash structure (e.g., crash pulse, deformation characteristics and intrusions). For supermini and small family categories, two models were generated in each class in order to describe the two main architectural/structural car variants that can usually be found on the road, i.e. with and without a lower load path in the frontal frame (structural elements below the main rails); the availability of both structural solutions in the GCMs is in fact important for the study of compatibility issues.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Section

In real world car-to-car crashes the interaction of the colliding partners is crucial. Thereby the interaction is controlled by the following three main parameters: vehicle mass, stiffness and geometry of the front structures. Together these parameters are the most important aspects for partner protection. With respect to the results of former research projects like VC-Compat the self-protection has still to be taken into account. The main objective of the ongoing research project FIMCAR (Frontal Impact and Compatibility Project) is to develop a proposal for a compatibility test procedure that addresses both: self and partner-protection. FIMCAR started in October 2009 and is co-founded by the European Commission within the 7th Framework Program. To achieve the main objective FIMCAR is mainly build on the results of VC-Compat. On this occasion FIMCAR improved the understanding of structural interaction and the capability of different test configurations (off-set and full width configurations) to assess frontal impact compatibility. To answer the open questions a large test program was executed that is divided into physical and virtual testing.

Besides the car models described in this section the following numerical models were developed or improved within FIMCAR project:

- Barrier models (PDB model, MPDB model, FWDB model)
- Multi body fleet models

Furthermore commercial models and in-house models of various barriers were used.

2 MODELLING APPROACHES

Within the FIMCAR project two different modelling approaches for the development of FE car models were used. The GCM (Generic Car Models) were developed by CRF (Centro Ricerche FIAT S.C.p.A.) and the PCM (Parametric Car Models) were developed by TUB (Technische Universität Berlin). The two types of models are available for three different crash solvers: LS-DYNA, PAM-CRASH and RADIOSS. In this way it is possible to include the detailed car models of the OEMs (which are partners of the consortium) into the virtual test program.

2.1 GCM - Generic Car Models

The GCMs used in FIMCAR were derived from the GCMs developed by CRF within the research project APROSYS [APROSYS 2005], through the implementation of huge modifications and improvements. In total five different models of three different vehicle classes (super mini, small family car and executive) were generated, Figure 2.1. Two additional variants, with respect to the original architectures of super mini and small family car, were in fact introduced by the addition (super mini) or removal (small family car) of a lower load path. The availability of such structural variants on the GCMs was an important and necessary element for the study and the understanding of compatibility issues within the project.

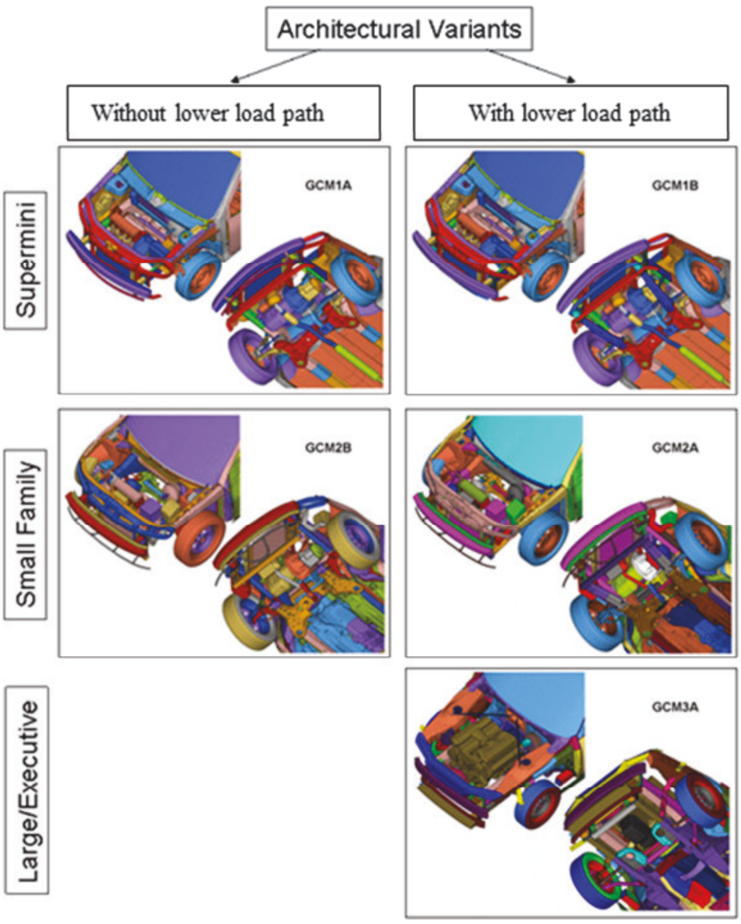
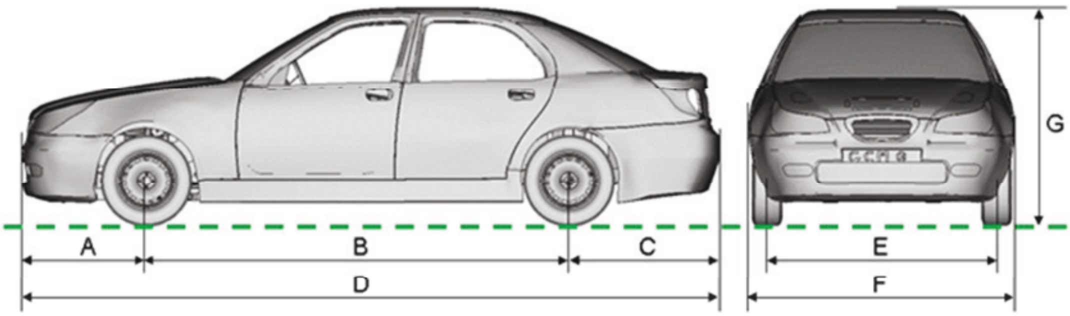


Figure 2.2: Architectural variants of GCMs.

A main requirement for the GCMs was to represent typical vehicles of the actual European vehicle fleet. Other than for the architectural solutions described before, this requirement was applied to the external dimensions and weights of the models, too.

Figure 2.3 gives an overview of the main external dimensions and weights of GCMs.



		GCM1A	GCM1B	GCM2A	GCM2B	GCM3A
A	*Front Overhang [mm]*	845		855		851
B	*Wheel base [mm]*	2464		2620		2887
C	*Rear Overhang [mm]*	603		742		1028
D	*Max Lenght [mm]*	3912		4217		4766
E	*Wheel track [mm]*	1507		1577		1578
F	*Max Width [mm]*	1720		1822		1828
G	*Max height [mm]*	1547		1485		1490
	Kerb Weight [kg]	983	988	1186	1180	1732

Figure 2.3: Dimensions and weights of GCMs.

Another important requirement taken into account during the GCMs development was to have frontal structures with main rails (or PEAS, Primary Energy Absorbing Structures) presenting cross sections with an adequate vertical overlap w.r.t. the “part 581 common interaction zone” (located between 16 and 20 inches from the ground), according to the TWG Voluntary Agreement Option 1 that is considered and applied in USA with the aim to improve the compatibility between SUVs/Pick-ups and traditional passenger cars. All GCMs comply indeed with this voluntary technical specification, as highlighted in Figure 2.4 (recalling graphically the rules behind the option and showing the GCMs positioning w.r.t. the part 581 zone).

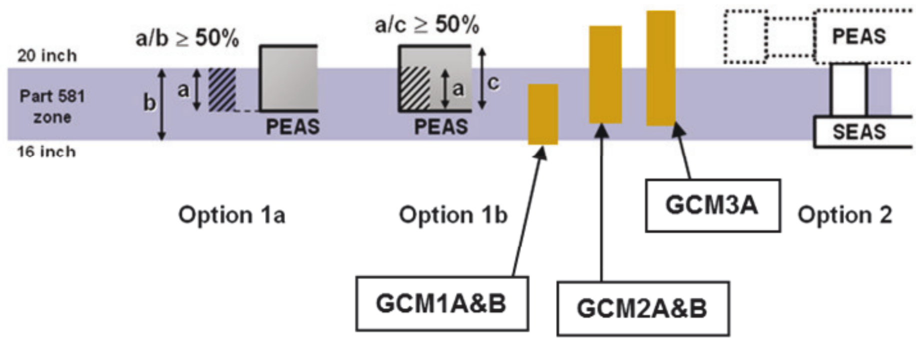


Figure 2.4: GCMs compliancy w.r.t. TWG Voluntary Agreement Option 1 (both 1a and 1b to be satisfied.

The modelling was controlled by the following two main parameters: high level of detail (comparable to models of OEMs) and a generic topology of structures and parts of typical vehicles that can be found on the roads of the corresponding vehicle class. To fulfil the first requirement especially the front structures of the GCMs were modelled with fine mesh. Thus the models consist of about 600,000 elements. Although the structures are generic ones they are modelled to ensure realistic crash behaviour with respect to crash pulse, intrusion behaviour, energy absorption management and collapse modes.

The development of the GCMs was performed by adopting the US NCAP (rigid wall, 56km/h, 100% overlap) and old AMuS (rigid wall, 55km/h, 50% overlap, 15° wall inclination; former test procedure of the German automotive magazine “auto motor und sport”) configurations as reference frontal impact conditions, see Figure 2.5.

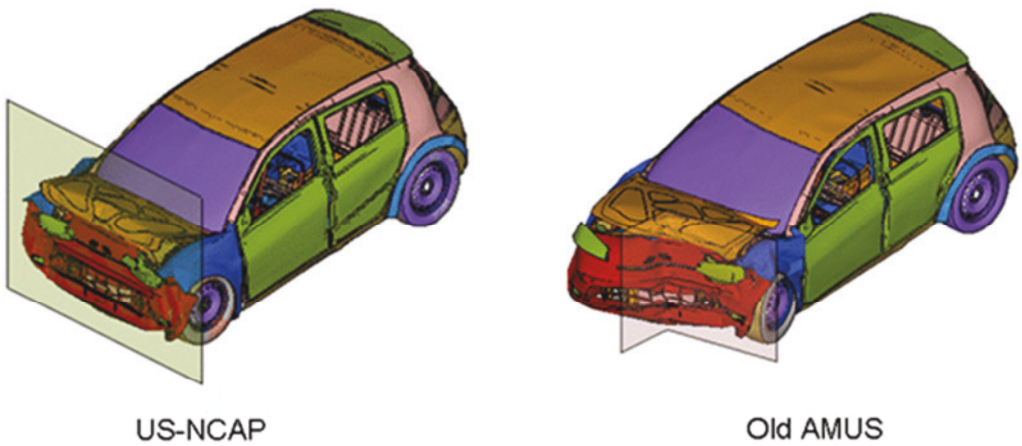


Figure 2.5: Frontal impact crash configurations considered for GCMs development.

The use of fixed rigid obstacle was decided in order to simplify the comparison of results between same GCM variant in different code environments, then avoiding the introduction of such an additional source of differences represented by the model of a deformable barrier.

In fact, all the GCM variants were initially developed/engineered within one of the three numerical codes (i.e. LS-DYNA); when the model variants behaviour reached the appropriate level of realism in the reference crash configurations, the translation to the other codes (RADIOSS and PAM-CRASH) was operated and the levels of correlation between code versions was verified.

A classical (or pure) validation phase (comparison between numerical and experimental results) cannot be strictly performed for these models, simply because corresponding physical models of GCMs do not exist; GCMs behave in a “realistic” manner; this “realistic” behaviour is indeed the target that guided their development work and that represents at the end their “validation”.

However, due to the fact that US NCAP data are available to the public and that the collision at 56 km/h against a rigid wall and 100% overlap represents one of the two development and verification virtual testing set-up used for the GCMs, a numerical-to-experimental comparison for this configuration was possible and done, on acceleration pulses, in order to better illustrate the level of “equivalence” between GCMs virtual results and the ones of similar state-of-the-art real vehicles. In Figure 2.6, the crash pulses obtained from the 3 numerical model code versions (red, blue and green curves) are compared with real (experimental) crash pulses of vehicles belonging to the same categories (grey dotted lines), for some of the GCM developed variants.

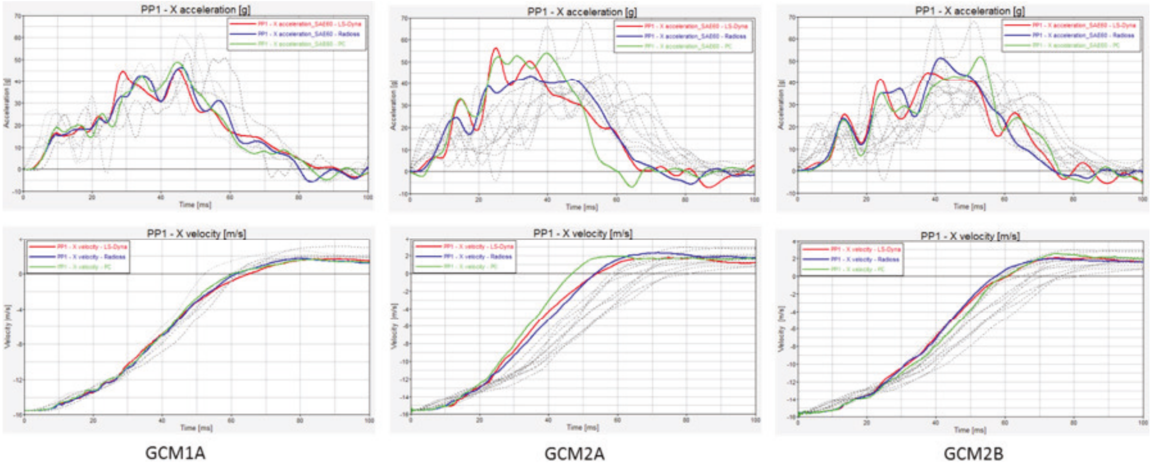


Figure 2.6: Comparison of crash pulses of some GCMs w.r.t. different code versions and real test results (US NCAP frontal impact at 56 km/h).

On each GCM model the user can find several measurement points from which acceleration pulses and/or displacements/intrusions can be extracted; the locations of these points correspond to the common positions typically adopted, on experimentally tested vehicles, for the accelerometers and the several markers; moreover, some sections of the vehicle structure are monitored on the models, so that the forces passing through them during the impact can be extracted for the analysis. Figure 2.7 shows the location of such monitoring points on GCM models.

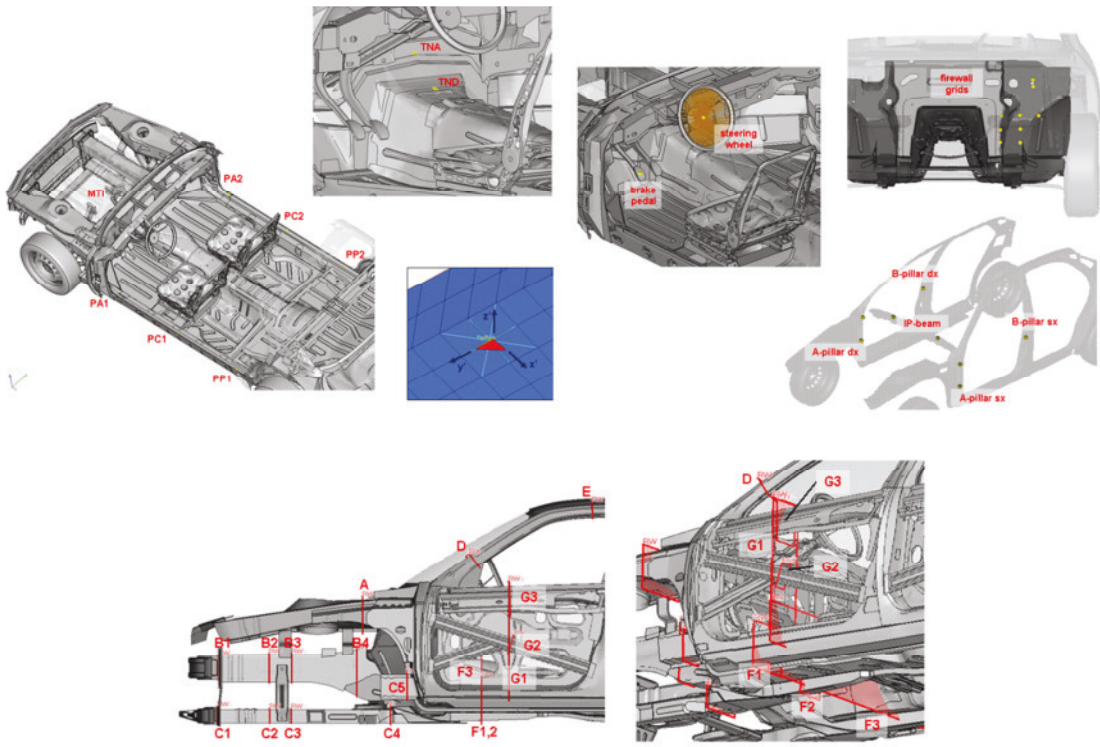


Figure 2.7: Typical locations of accelerometers, markers and cross sections available on GCM models.

The main tasks of the GCMs within FIMCAR are to analyse the crash behaviour in the different frontal impact test configurations, to compare these results with responses from car-to-car crash simulations and to serve as common bullet vehicles against the OEM models.

In Figure 2.8 the main crash configurations considered during the project are recalled.

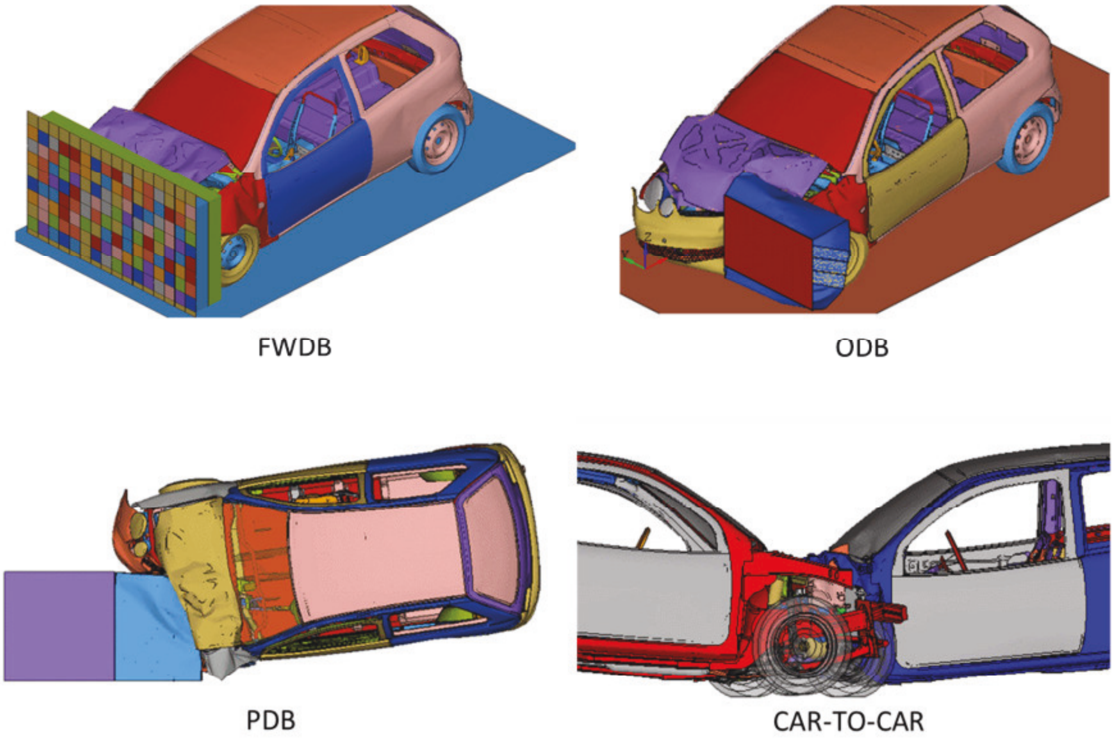


Figure 2.8: Main frontal impact configurations considered within FIMCAR.

2.2 PCM – Parametric Car Models

To investigate the influence of different front structure topologies and the impact of the assessment metrics to the front structures, the PCMs were developed to overcome the aims of structural interaction. Usually the modification of the structure of a finalised FE model is a complicated and time consuming exercise. Morphing tools or manual transformations of the mesh is time consuming and can cause numerical instability. To avoid these problems, the PCMs approach uses an implicit parametric design of a CAD model that allows fast modifications of the structure. Therefore position, shape and size of the most important crash structures can be changed in an efficient way. Finally an automated mesh algorithm generates meshes and additional FE information needed to create computable FE models without further pre-processing [Stein 2011].

In contrast to the GCMs one of the main requirements of the PCMs was the lower calculation time. To comply with this, the PCMs were simplified. E.g. many parts of the power train were merged to one rigid part, and crash relevant parts like cross beam, longitudinals and sub frame were modelled with respect to realistic crash behaviour, Figure ***2.9***.

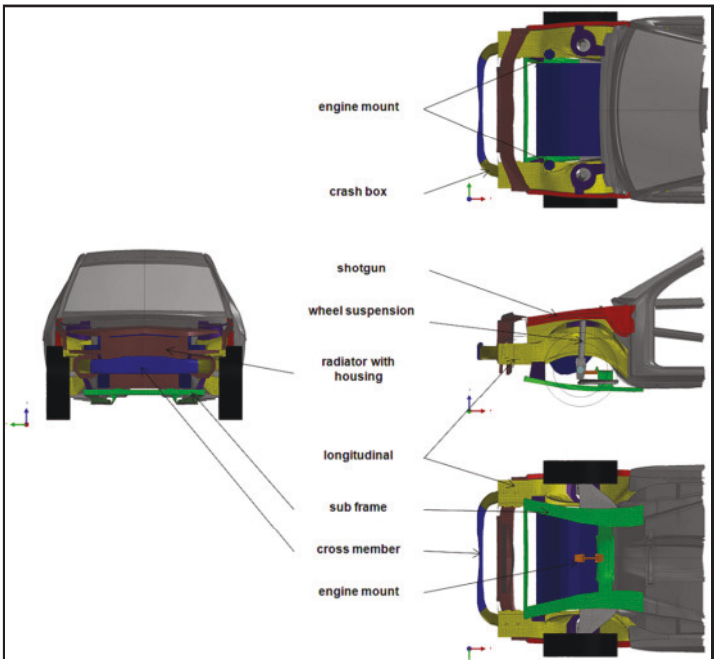


Figure 2.9: Front end structures of the PCMs.

During the first part of the FIMCAR project three different vehicle classes (super mini, large family car and executive) were modelled. To reduce the computational effort, the mesh size was set to an average edge length of 15mm. The final number of elements is about 200,000 for each vehicle model. One of the main requirements, when setting up the models was to represent the actual European vehicle fleet. Therefore averaged values for the most crucial design parameters (vehicle length and width, wheel base and kerb weight) were investigated by using the values of four to six top sellers for every vehicle class, see Table 1.

Table 1: Target values for the geometry of the PCMs.

	length [mm]	width [mm]	wheel base [mm]	kerb weigth [kg]
Super Mini	3,800	1,670	2,400	843
Large Family Car	4,600	1,820	2,800	1,568
Executive	5,100	1,910	3,030	1,899

The topology of the structures, especially in the front end of the vehicle, is based on the construction methods of real vehicles. In combination with the specific stiffness (material and part thickness, shape of the cross section) the vehicles behave during the crash in a realistic way. However the models are not able to represent failure of materials or welding points.

The priority of the behaviour of the structures and the interaction increases in car-to-car collisions. To make a statement about compatibility issues, it is important that the models have the ability to produce several phenomena, like over- and under riding. Modifications which finally lead to a validated status of the PCMs were always done with respect to these criteria.

The models were validated for the US NCAP configuration (rigid wall, 56km/h, 100% overlap). The crash pulse of the compartment was the main criteria in the validation process. The pulses were compared (duration, peak and average deceleration) with real crash pulses of cars of the corresponding vehicle class. Therefore the FIMCAR database and other public available databases were used to find a range of pulses for the different car types. The number of test objects ("TO" in Figure 2.10) that could be found differs for the three models.

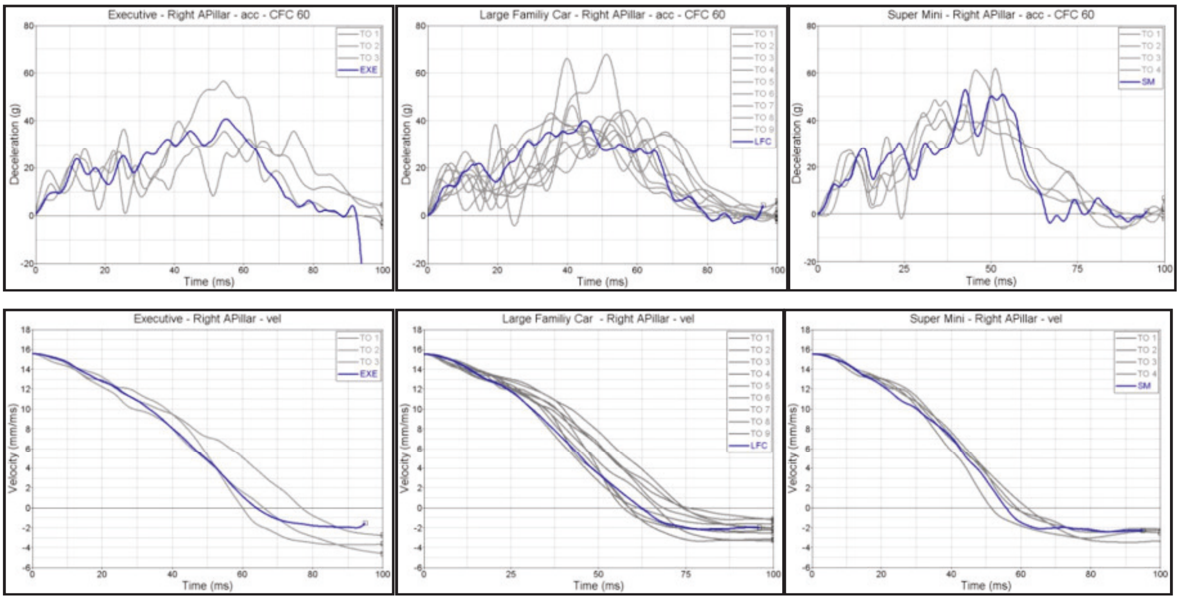


Figure 2.11: Comparison PCMs vs. European cars.

Furthermore the pulses of the different crash codes were compared and validated in order to assure, that the models can be used for the same investigation at OEMs that use different crash codes. The comparison is shown in Figure 2.10.

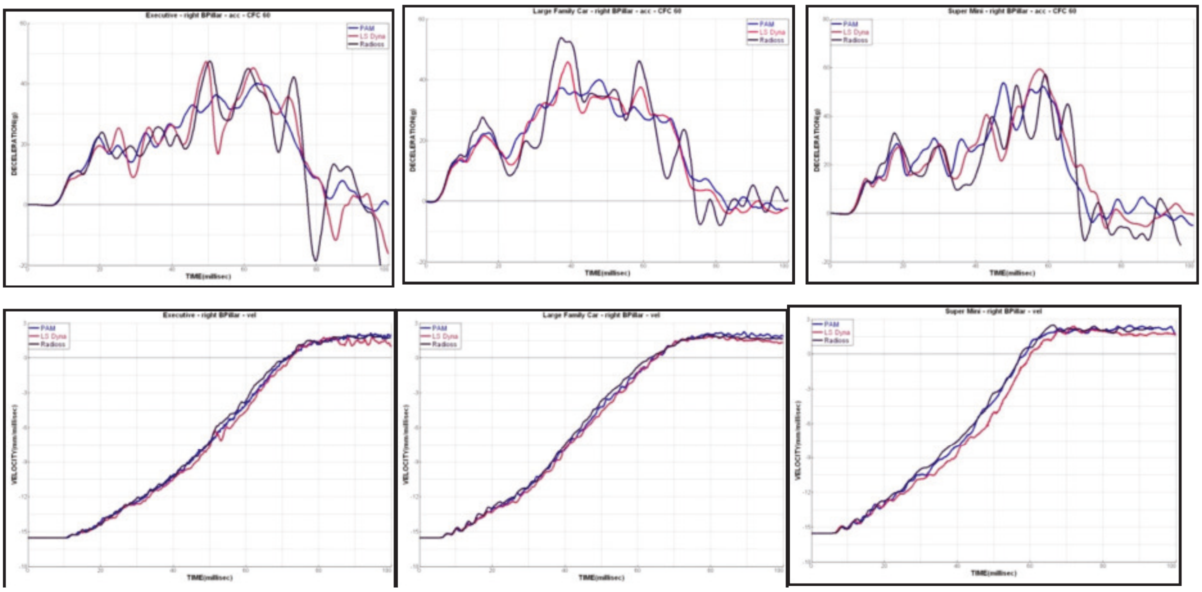


Figure 2.12: Comparison of the different crash codes for the PCMs.

The PCMs offer several ways to measure intrusions. All relevant structures, like bulkhead, floor pan, or the side frame structure, are modelled with deformable material characteristics. Due to the simplifications of the model it was not possible to represent a detailed passenger compartment (e.g. no steering wheel or foot pedals were modelled). During the validation the intrusions were used to adjust the force levels in the front end structure and the passenger compartment. The aim was to prevent the collapse of the passenger compartment.

The main tasks of the PCMs within FIMCAR are sensitivity analyses of the topology of structures in car-to-car crashes and robustness analyses of the test configurations and their corresponding assessment metrics.

2.3 Assessment of Occupant Loading

The main intension of both model approaches is to analyse the influence of the front structures in different crash scenarios. Due to the modifications of these structures the crash behaviour changes. Because normally the characteristic of a restraint system (trigger times, load levels etc.) is designed for a specific crash behaviour of the vehicle, the restraint system has to be adjusted after each modification of the structure to ensure an optimal safety level. For that reason the models are not equipped with restraint systems and do not offer the possibility to include crash test dummies to measure the loads that are applied to the occupant during the crashes.

However, an assessment of the occupant loading is crucial. To overcome this problem, different methodologies were used within FIMCAR to analyse the loading of the occupant.
In the full width test configurations the OLC (Occupant Load Criterion) was used to correlate the deceleration of the cabin to the loading of a belted occupant [Kübler 2008]. The OLC is a mathematical algorithm that simulates an artificial restraint system. This restraint system has a belt slack causing 65mm free forward displacement relative to the vehicle. After that a constant deceleration of the occupant is assumed on the remaining 235mm forward displacement. The constant deceleration is the OLC and corresponds with the injury severity level of the occupant.

In the offset test configuration the analyses of intrusions (firewall and a-pillar) into the cabin provides information of the loading of the occupant. Assessments of the injury severity level caused by intrusions are supported by analysing the loads monitored in relevant cross sections of the structures.

3 FIELD OF APPLICATIONS

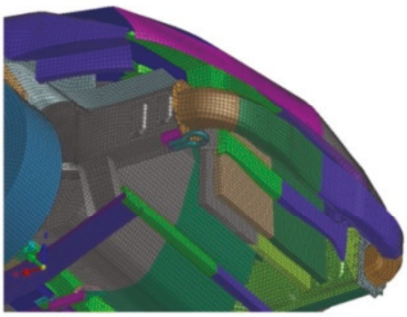
At this point chosen applications of the two types of models are presented. Depending on the aims of each investigation both model approaches were used at the same time or the analysis based on one or the other. To assess the capability of the two test candidates for the full width test configurations (full width rigid barrier – FWRB and full width deformable barrier - FWDB) all investigations were performed for both configurations.

3.1 Possibilities of Influencing the FWB Criteria in Full Width Tests

In principle test procedures must meet a lot of technical requirements like reproducibility and repeatability. Furthermore the assessment metrics shall bring benefits e.g. shall improve the safety level. In terms of FIMCAR the full width tests focus on improving the structural interaction of colliding cars in frontal impacts. The assessment metrics analyse the forces applied to the load cell walls (LCW) which are generated by different structures of the front end of the car. To ensure that these forces were applied by structures that help to improve the structural interaction of cars in frontal impact an analysis was performed to investigate the influence of hard points (like towing eyes or the towing eye attachment) to the force criteria.

3.1.1 PCM - Towing Eye in FWRB and FWDB

In a first step a PCM was equipped with a towing hook mounted at two different positions (upper and lower side) of the right longitudinal, see Figure 3.1. The towing eye was simplified and designed by several assumptions (e.g. mass of towed vehicle 1500kg, safety factor 2, material steel, only normal stress). The towing eyes were in alignment with Row 5 (mounted on upper side) and Row 3 (mounted on lower side) of the LCW.



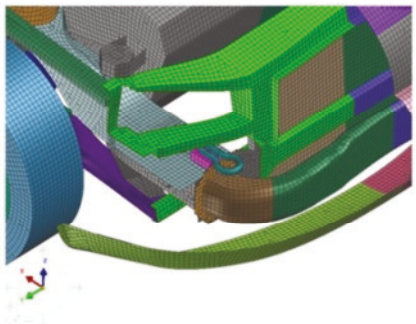


Figure 3.1: Mounting positions of the towing eye on right longitudinal (left figure – below longitudinal; right figure - above longitudinal).

In the FWRB test configuration the unfiltered sum forces of the Rows 3 and 5 showed a high peak (red circles) at the time of impact of the towing eye with the wall, see Figure 3.2. Due to the recommended filtering of LCW data with a CFC60 filter this peak disappears.

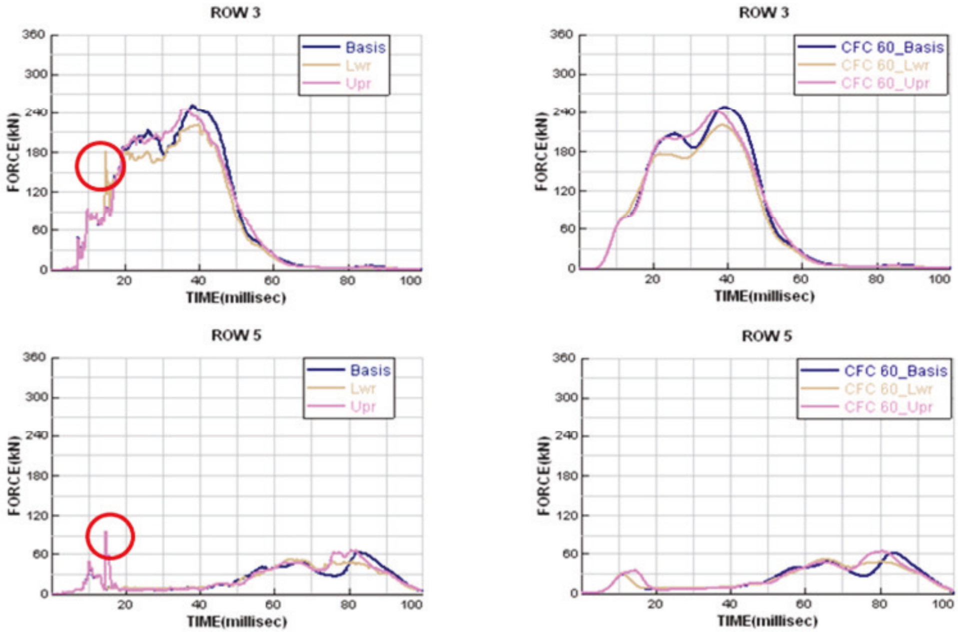


Figure 3.2: FWRB – LCW forces of Row 3 and 5 (left side unfiltered, right side filtered with CFC60) applied by PCM with towing eye.

In general it could be shown that hard points like the towing eye apply heavy loads to the LCW. But the effect disappears after filtering the data. In that way the assessment criteria of the FWRB were not influenced by hard points.

The same simulations were conducted for the FWDB test configuration. In contrast to the FWRB the towing eye influenced the criteria of the FWDB. The applied forces did not disappear after filtering, see Figure 3.3.

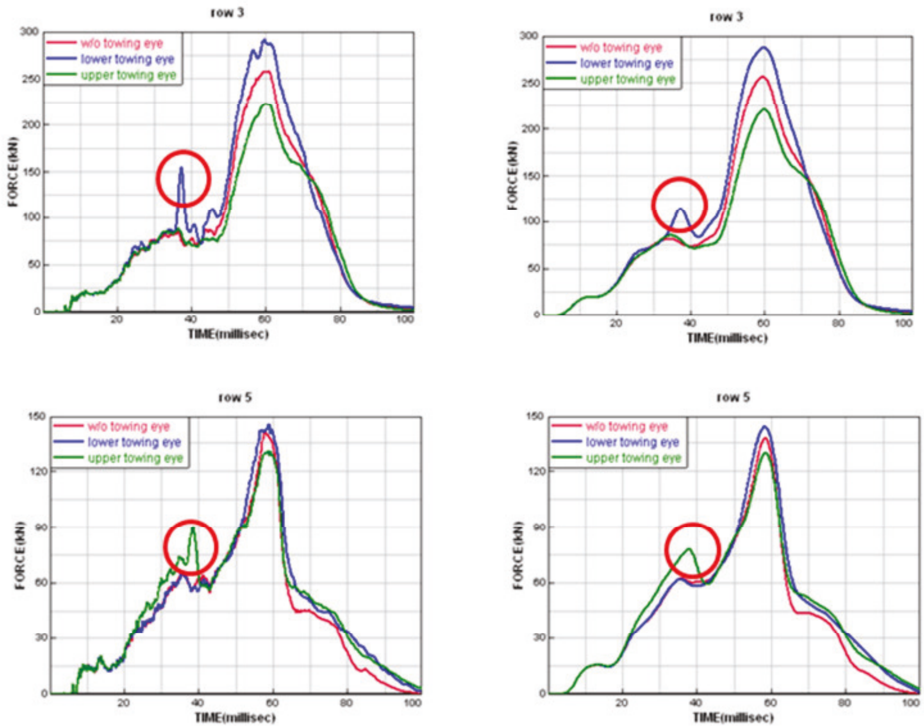


Figure 3.3: FWDB – LCW forces of Row 3 and 5 (left side unfiltered, right side filtered with CFC60) applied by PCM with towing eye.

In the crash against the FWDB the relatively stiff towing eye showed another deformation behaviour due to the deformable element in front of the LCW. In that way the towing eye itself bended (lower towing eye) or the longitudinal bended (upper towing eye) and applied significant forces to the LCW, see Figure 3.4.

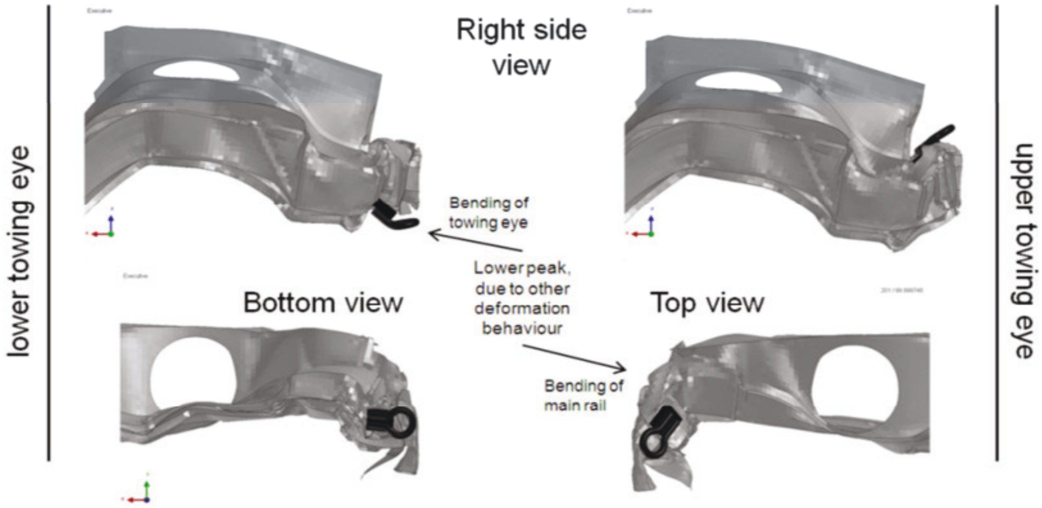


Figure 3.4: FWDB – change of deformation mode of longitudinal for towing eye mounted on lower side and upper side of longitudinal.

3.1.2 PCM - Towing Eye Attachment in FWRB and FWDB

Due to styling aspects and increased requirements on pedestrian safety today vehicles are only equipped with a screw thread to attach the towing eye to the car. Following this the PCM were equipped with such an attachment at two different locations, Figure 3.5.

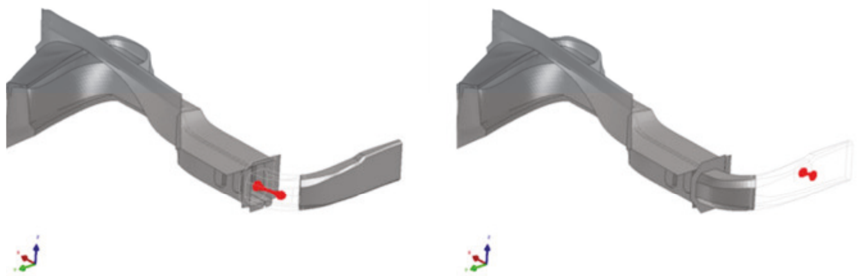


Figure 3.5: Screw thread attachment (left figure – in front of longitudinal; right figure – on the right half of the cross beam).

Both configurations were crashed against the FWB test configurations. Compared to the analysis of the LCW of the FWRB the data showed hardly any differences in the forces applied to the wall. In the FWDB configuration the criteria were influenced by the screw thread.

Finally the simulations showed that the deformation behaviour of the front end structures and therefor the force distribution to the wall is different in the two test procedures. Furthermore it could be shown that a high local stiffness lead to different deformation behaviours in the two configurations. This changed deformation mode has no influence on the FWRB criteria but they influence the FWDB criteria.

3.1.3 GCM – Towing Eye Attachment in FWRB and FWDB

To improve the understanding of the influence of a towing eye attachment the GCM were used to repeat the conducted simulations. The GCM is equipped with a rigid screw thread located inside of the crash box and mounted on the frontal flange of this crash box, see Figure 3.6.

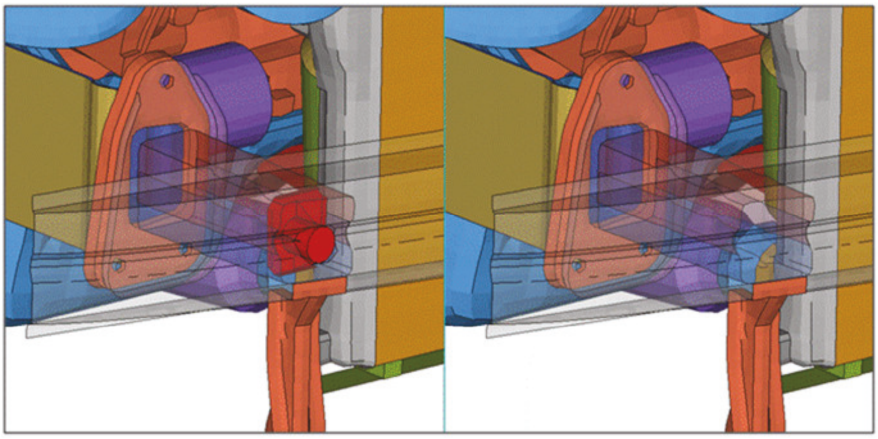


Figure 3.6: GCM1A – Right front crash box with (left figure) and without (right figure) screw thread attachment.

The GCMs were crashed against FWRB and FWDB with and without screw thread attachment. In the FWRB configuration the LCW data showed no differences between the GCM with and without screw thread, see Figure 3.7.

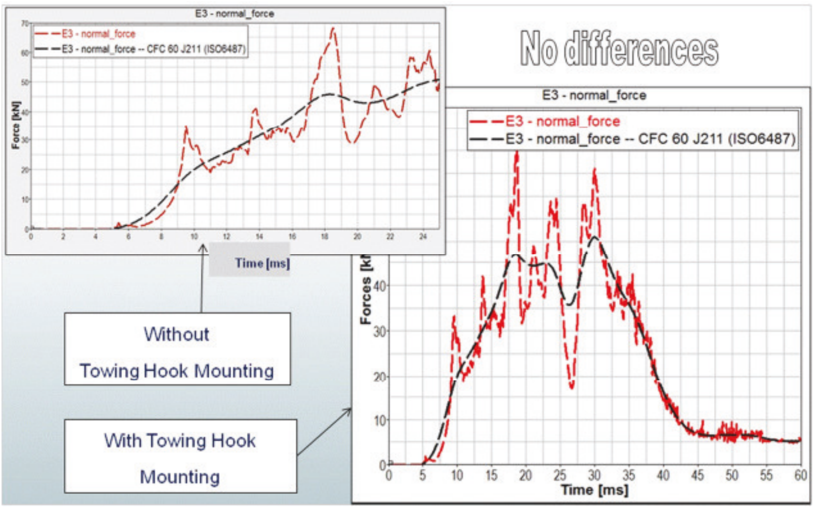


Figure 3.7: FWRB - force applied to directly impacted load cell (left side without, right side with towing eye attachment).

In the FWDB test the deformable element caused only very slight differences in the deformations of the crash box depending on the existence of the attachment. Without the attachment, the crash box still bends downwards (instead of collapsing axially with folding like against the FWRB, with just a different fold detectable on its side wall, see Figure 3.8 (red circles). This initial slight difference on the crash box induces also a subsequent slightly different collapse fold on the main rail side wall (white circles)

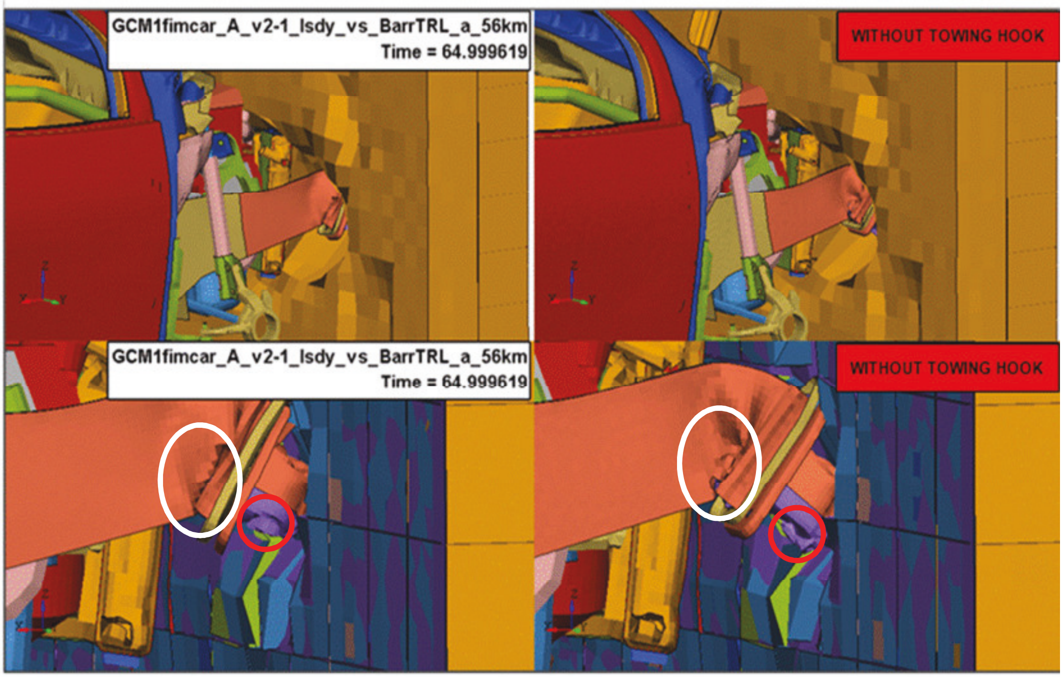


Figure 3.8: FWDB - GCM1A with and without screw thread attachment.

The above mentioned differences in the deformation mode slightly influence the forces applied to the LCW. Figure 3.9 shows the total wall force and the sum forces of Row 3 and Row 4 of the GCM with (dotted lines) and without (solid lines) towing eye attachment. In comparison the forces applied by the GCM with a screw thread are a little bit lower than without the screw thread especially in the range up to 40ms (time range of the FWDB criteria). However the differences had no influence to the assessment criteria.

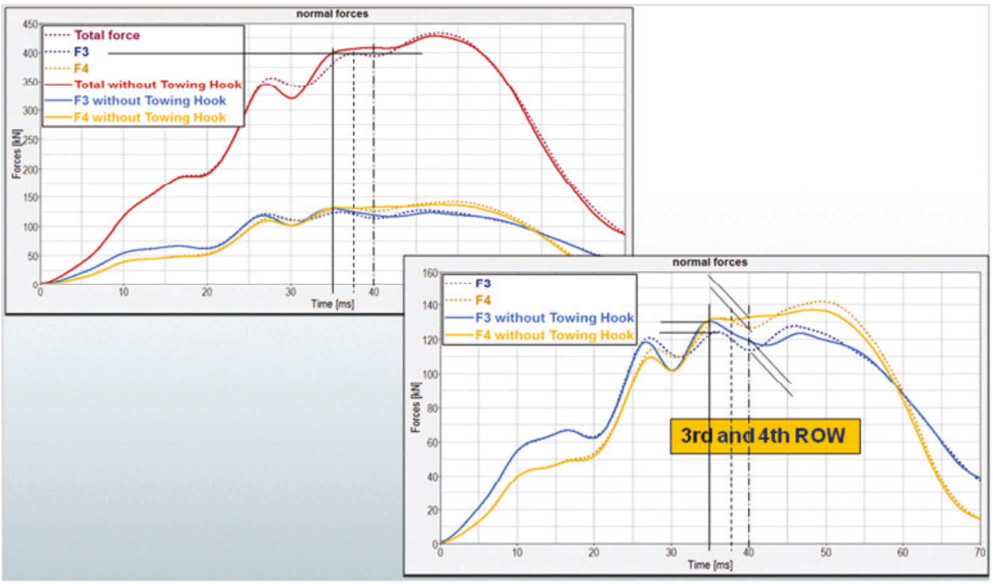


Figure 3.9: FWDB – total wall force and Row 3 and Row 4 forces applied to LCW by GCM1A with and without towing eye attachment.

3.1.4 Conclusions Possibilities of Influencing the FWB Criteria in Full Width Tests

The conducted simulations showed that the deformation of structures differs depending on the test procedure. The deformable element of the FWDB causes the structures to other deformation modes. W.r.t. the main objective of this analyses it could be shown that parts with a high stiffness attached very far forward to the vehicle front can have an influence to the force criteria depending on the test procedure. In the FWRB the effects disappears after the filtering whereas the criteria of FWDB detects this local high stiffness. However in case of the towing eye it could be shown that the todays commonly used attachment does not influence the criteria of both test procedures. Furthermore it was shown that the presence of towing eyes may influence the deformation pattern of the car. Following that it is natural that the load forces may be different.

3.2 Cross Beam Height and Position Relative to Longitudinal

In general the topology of the crash energy absorbing structures is similar across all cars. As a result the topology of the primary energy absorbing structures (PEAS) is in almost every case as the following: crossbeam connected with crash boxes to the longitudinals. However there are cars that have other topologies of the PEAS (e.g. HONDA CRV has its cross beam below the longitudinal). The main objective of this study was to investigate the behaviour of those designs and to decide if those PEAS are appropriate in car-to-car crashes.

3.2.1 Modifications

Additionally to the basis configuration of the PCM (executive) five modifications were modelled. The modifications followed the goal of this study to investigate a PEAS topology where cross beam and longitudinals were not in vertical alignment. Table 2 lists the modifications and Figure 3.10 gives an overview about the different designs.

Table 2: PCM structural modifications

Modification (abbreviation)	Description
mod_1	Increase the vertical position of the longitudinals and cross beam until the vehicle fails the metric
mod_2	Lowered cross beam and variations of connections and stiffness of the structures (cross beam below and within main rails)
mod_3(_1/2)	Cross beam below main rails, but in front of them, different connection stiffness
mod_4	Lowered cross beam (misalignment of structures)
mod_5	Same configuration like mod_4, but placed as far forward as possible

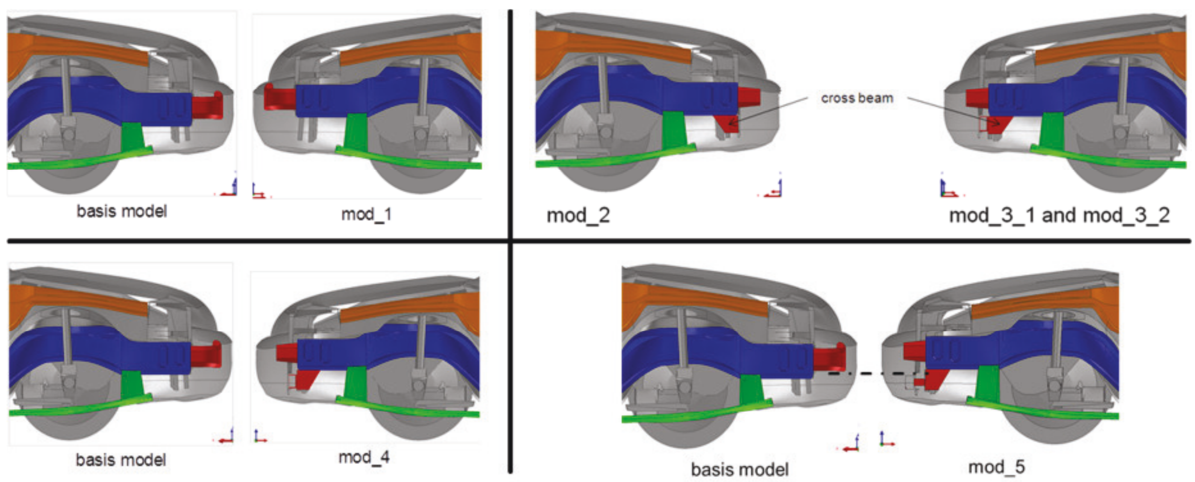


Figure 3.10: PCM structural modifications.

With respect to the LCW the different heights of the energy absorbing structures in combination with the alignment with the part 581 zone (common interaction zone) is shown in Figure 3.11.

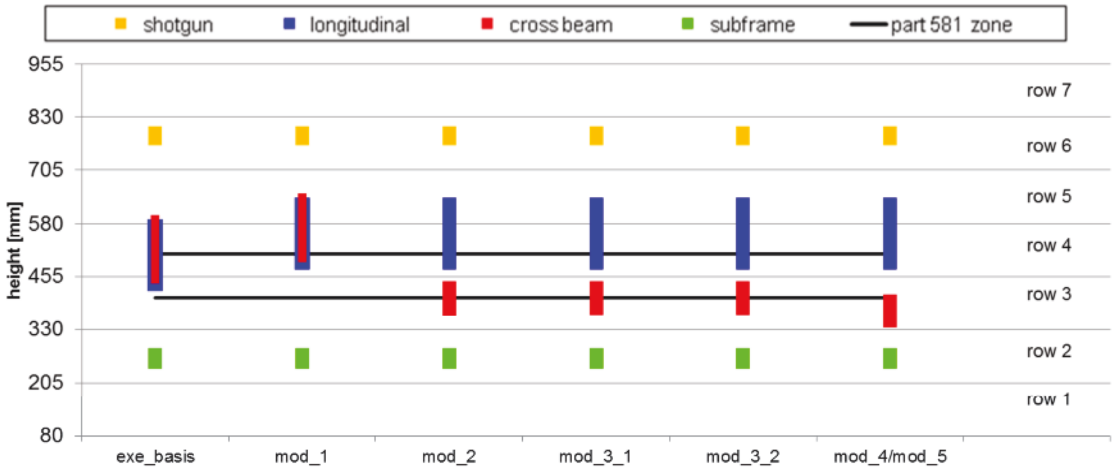


Figure 3.11: PCM – Height of energy absorbing structures.

3.2.2 Results

All described modifications were crashed against the FWRB and the FWDB. Different observations were made after the analysis of the both force criteria:

FWRB:

- The total wall force of 200kN was reached later (10ms ➔ 17ms) for the modifications compared to the basis model
- Modification 3 (compared to modification 2 the cross beam was placed in front of the longitudinals) could apply enough forces to pass the criteria, however the values were borderline between pass and fail
- Modification 4 as well as modification 5 could not apply enough forces to the LCW to pass the metrics

FWDB:

- The wall force limit of 400kN was reached later (37ms ➔ 44ms) and no engine dump occurred
- Only the basis model passed all proposed metrics, modification 2 only failed the force depended metric but passed the time depended ones (final metric proposal)

Comparing the results of the two analysis differences were identified in the deformation behaviour of the primary energy absorbing structures (PEAS). The deformable element forces the structures to deform earlier in the crash. Different bending modes and thus other reaction forces on the wall are the result.
Concluding the results of this analysis it was found that different structural designs were assessed by the two test procedures in different ways. While the FWRB assessed the weak structures as good enough to pass the metric the FWDB detected these design as not being appropriate. The main reason for that assessment was the honeycomb structure in front of the wall in the FWDB test configuration.

3.3 Step Effects

The objective of the FIMCAR full-width assessment procedures is to assess the car's safety performance with respect to structural alignment. For robust metrics the influence of impact alignment shall not result in step effects, i.e., small changes in the ride height causes large differences in the metric results. Here step effect means that the metrics shall reflect the cars structural topology in particular the PEAS. Furthermore the criteria shall correlate well with those structures and should let vehicles pass respectively fail the metrics depending on their performance in car to car crashes. The goal of this analysis was to investigate the robustness of the metrics in terms of step effects and to ensure the correct assessment of the metrics.

3.3.1 Methodology

The PCM large family car was used for this analysis and in a first step crashed against the FWRB and the FWDB. Therefore different ride heights were simulated by vertical translation of the barriers. Figure 3.12 shows the initial structural alignment with the LCW and gives an overview about the overlap of Row 4 (71%) and Row 3 (54%). A step size of 20mm was chosen.

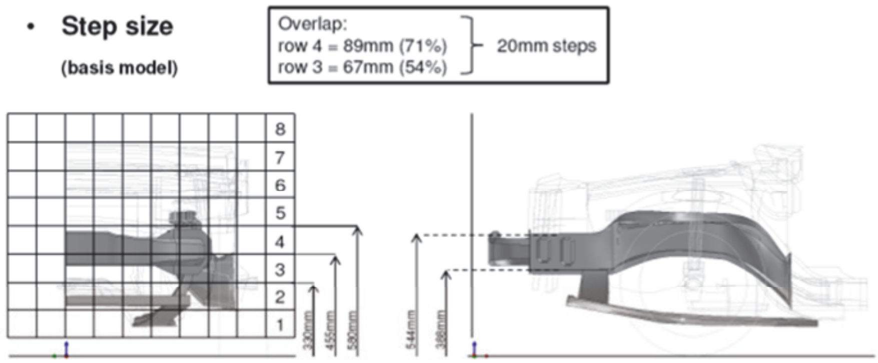


Figure 3.12: PCM – initial structural alignment with the LCW.

3.3.2 Results of FWB Tests

The results of the FWRB crashes can be seen in Figure 3.13. On the left side the figure shows the ratio of the Row 4 force to the sum of the forces in Row 3 and Row 4 (F4/(F3+F4)) and the overlap of the PEAS with the corresponding rows. The figure on the right side shows the individual row forces (Row 3 and Row 4) related to the geometry of the cars. A good correlation between the applied wall forces and the corresponding structural alignment with the loaded rows can be observed (left figure). Furthermore no strong step effects could be identified. The right figure shows the forces (e.g. force of Row 4 is zero if there is no overlap with a structure) depending on the overlap of the PEAS with Row 3 and Row 4.

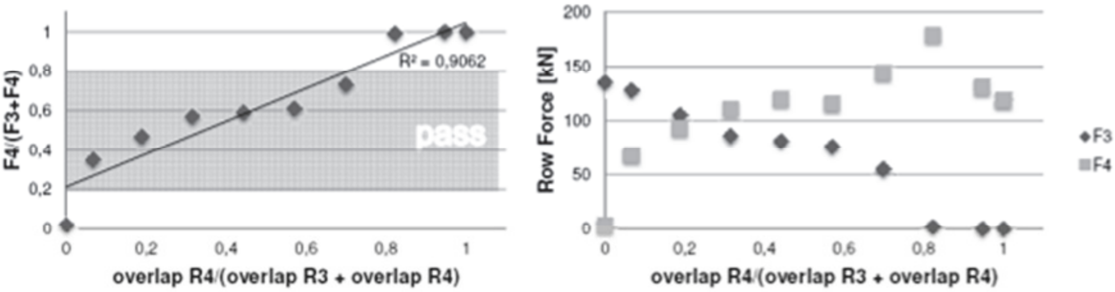


Figure 3.13: FWRB – Influence of ride height on forces in Row 3 and Row 4;), left picture shows the relation of Row 3 and 4 from the FWRB metric, right graph shows the individual forces of Row 3 and 4.

The results of the FWDB simulations are shown in Figure 3.14. With respect to the different metrics the figure on the left side shows the individual forces (Row 3 and Row 4) up to a total wall force of 400kN and the figure on the right side up to 40ms. Due to numerical problems of the FWDB barrier model the simulation with the PCM raised by 40mm terminated before 40ms. Thus no assessment by the time dependent metric could be made for this run. Both criteria show no step effects and a good correlation to the structural topology. However load spreading due to the deformable element could be observed.

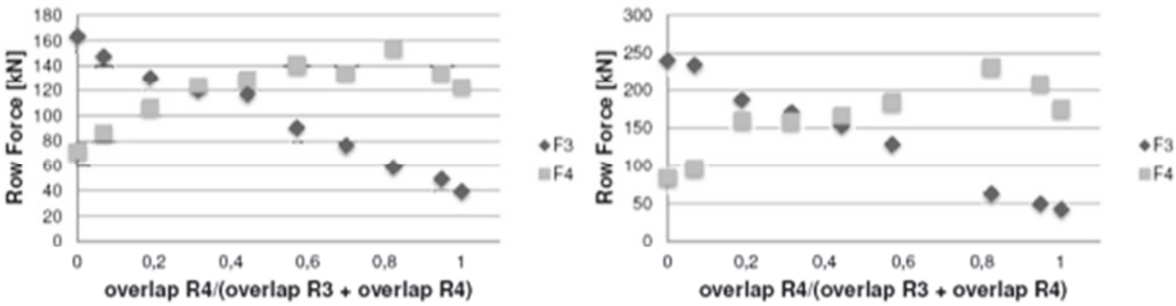


Figure 3.14: FWDB – Influence of ride heights on forces in Row 3 and Row 4; left graph shows the row forces up to LCW force 400 kN, right graph shows the row forces up to 40 ms.

3.3.3 Car-to-car Crashes

To compare the ratings of the metrics car to car crashes were conducted with respect to the test results of the FWRB. The following three configurations were simulated:

- Lowered vehicle that fails the metric against basis model ➔ vertical offset -40mm
- Raised vehicle that fails the metric against basis model ➔ vertical offset +60mm
- Borderline (lowered and raised) vehicles that passes the metric ➔ vertical offset 100mm

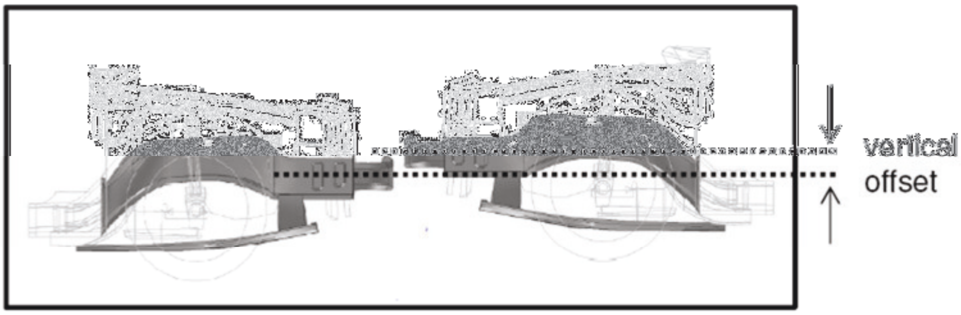


Figure 3.15: car to car crashes – definition of vertical offset.

The tests were conducted with 50% and 100% horizontal overlap and a closing speed of 112km/h (each vehicle with 56km/h).
The results of the full overlap simulations were that the overriding car had lower peak values for the deceleration of the cabin and the intrusions of the firewall increases of the underridden car. These trends could be validated by increasing the vertical misalignment of the PEAS. The more the misalignment increases the more increases the incompatibility.
For the 50% overlap simulations there were hardly any differences for the deceleration detected. No trends could be observed for the firewall intrusions. A comparison of the a-pillar intrusion showed higher displacements for the underridden car then for the opposing car.

3.3.4 Conclusions Step Effects

The robustness analysis of the FWB assessment metrics showed good results. Although the resolution of the LCW is limited (125mm x 125mm) no step effects could be observed within the given range. A good correlation of the measured forces and the structural alignment with the rows of the LCW could be verified. The car to car simulations indicate that cars that fail the metrics also perform worse in car to car crashes compared to those that pass the metrics. The identified thresholds of the different metrics seemed to work well.

3.4 Test Severity

As shown in the accident analysis of FIMCAR [Johannsen 2011] the main injury risk (MAIS2+) in frontal impact with more than 75% overlap occurs with a delta-v up to 52 km/h taking into account the exposure and the individual risk. Following this the capability of the FWB tests procedures in particular the FWDB was analysed regarding different test speeds. The main objectives of this study were to check if the metrics results are independent from the test speed within a given range.

3.4.1 Methodology

For this study the GCMs (GCM1B, GCM2A and GCM3A) and PCM (large family car) were crashed against the FWRB with 56km/h and FWDB with 40km/h, 50km/h and 56km/h.

3.4.2 Results

A final analysis of the assessment metrics showed that all proposed FWDB metrics worked well for different test velocities. However for the time dependent criteria with fixed limits were borderline due to the fact that the wall forces increase slower due to the lower test speed.

3.4.3 Conclusions Step Effects

The results of this analysis showed that the selected assessment metrics for the FWDB test procedure are independent from test speed in a range from 40km/h to 56km/h. A reduction of the test speed for the FWDB test to address the higher risk of MAIS2+ injuries seemed to be possible.

3.5 Other Use Cases for the FIMCAR Car Models

The models were used for several other applications in the project such as sensitivity analysis of different PDB metrics, PDB test severity analysis, assessment of lower load path designs etc. These investigations are reported in detail in the FIMCAR Deliverables D2.1 [Lazaro 2013/1], D2.2 [Lazaro 2013/2], D3.1 [Adolph 2013/1], D3.2 [Adolph 2013/2], D4.2 [Versmissen 2013].

4 SUMMARY

This section gives an overview about the two main car FE modelling approaches used within FIMCAR to investigate car-to-car frontal impact and corresponding test procedures that allow assessing self and partner protection. On the one hand the Generic Car Models (GCMs) were used, these models were developed originally within APROSYS by CRF and subjected to huge modifications and improvements for the goals within FIMCAR. The GCMs represent cars of three different vehicle classes with a generic structure and topology of the most common parts of the front end of modern cars. The level of detail is comparable with those of OEM models used for the product development process. On the other hand the Parametric Car Models (PCMs), developed by TUB, were used. These models are simplified models of three different vehicle classes. One of the main results of the simplification process was the separation of the energy absorbing structures of the front end. Due to the parametric design of the CAD model fast changes in the topology of the structures are possible.

Five chosen investigations were presented demonstrating a large field of applications of the both models. The first example shows the usage of the both models to investigate the influence of specific structures like the towing eye respectively its attachment to the full-width barrier metrics to avoid a wrong assessment by the developed metrics.

Different designs of the primary energy absorbing structures could be analysed by the PCMs. Structural modifications were crashed in full-width barrier tests and analysed with respect to their capability in car-to-car crashes.

The third and the fourth example show how the numerical models helped to develop the test procedures. The metrics were analysed regarding robustness to avoid step effects and to check the identified pass and fail thresholds. Furthermore the test severity was analysed with respect to a reduction of the test velocity and the effects to the assessment metrics.

The final example shows a sensitivity analyse of the vehicle parameters like mass, test speed and topology of specific structures for the PDB test procedure. 45 simulations were conducted to investigate the influence to the assessment metrics.

5 CONCLUSIONS AND OUTLOOK

Within the FIMCAR project a large test program was executed that was divided into physical and virtual testing. Two different FE model approaches were used to support the investigations. Depending on the approach different tasks were performed to answer open questions and improve the understanding of frontal impact. It could be shown that today the quality of the results of the virtual models is on such a high level that it could be used for research purposes. In that way the number of physical tests and therefore costs could be reduced.

The intension of different approaches follows the need of different levels of details. On the one hand simplified models like the PCMs can be used for the identification of the influence of different EAS topologies. Due to the relatively low number of elements they are suitable for high numbers of simulation runs. They are offering the possibility of optimising the structures for car-to-car crashes and for the assessment metrics. In that way the PCMs offer the potential to identify the best structural concept to improve frontal impact compatibility.

On the other hand the GCMs are closer to real cars and the level of complexity allows detailed analyses of the structural interaction of all parts of the front end. For the future the generic design offers the option to serve as bullet cars within the product development process by using them to improve the vehicle safety or in terms of virtual testing for homologation replacing the homogenous honeycomb barriers.

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FIMCAR
V – Off-set Test Procedure: Review and Metric Development

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The off-set test is the most common test procedure in vehicle crash testing. These procedures are currently used in the European frontal directive (96/79/EC) and in consumer tests like Euro NCAP, IIHS, etc. In both compulsory and consumer testing cases, the ODB test consists of an impact into a honeycomb barrier (EEVC barrier) with a 40% overlap.

The current ODB procedures only assess the self-protection of the tested vehicle. There are no methodologies investigating the partner-protection (e.g. structural interaction or frontal force levels) using these test configurations.

Another off-set test procedure – the Progressive Deformable Barrier (PDB), a 50% off-set test – has been investigated for structural interaction and frontal force level assessment. The PDB is considered as the most promising off-set test procedure to assess partner-protection issues.

In the PDB test, the deformation of the honeycomb barrier can be measured after the test. The PDB honeycomb is stiffer than the EEVC barrier and becomes progressively stiffer with increased deformation. The barrier 3D deformation profile is used to analyse the structural interaction and force levels of the tested vehicle. The PDB assessment procedure shall use the barrier deformation as an input.

The specific objective of the deliverable is to define the fundamental concepts for developing assessment criteria and associated performance limits for the off-set test procedure.

In an initial phase, existing test procedures have been investigated and an initial assessment methodology has been developed. This includes the review from past compatibility research projects and review of current test protocols. The robustness of the assessment criteria is investigated and potential for misuse in vehicle design is identified.

Full scale tests and simulation studies were performed to investigate topics like robustness, repeatability and reproducibility of the test and the assessment criteria. Existing Euro NCAP tests performed in recent years were used to support this investigation.

Based on the results of the tests performed, different proposals for criteria and limits have been investigated. Although the PDB is a promising procedure to evaluate compatibility issues such load spreading, at this stage of the project the criterion was not possible to be fully developed.

For this reason the ODB is proposed as off-set test procedure, the ODB procedure will maintain the current self-protection requirements. However, PDB might still be an option for the future when validated compatibility metrics can be proposed. Therefore, the FIMCAR consortium agreed to further develop PDB criteria.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to describe the test procedures and assessments to evaluate self and partner-protection as defined in compatibility. The crash test and simulation results and analysis performed to develop the assessment criteria will be also included. The assessment will consist of performance criteria, metric and limits for evaluating the frontal compatibility using the off-set test procedure.

1.3 Structure of this Deliverable

In the beginning possible candidates for the FIMCAR off-set test procedure are described and evaluated following a pre selection of the FIMCAR off-set test procedure. Chapter 3 describes the development of the initial development of the Off-set assessment criteria development followed by a review of available test results in Chapter 4.

2 PROPOSAL FOR OFF-SET TEST PROCEDURE

2.1 Review of Existing Procedures

2.1.1 Off-set Deformable Barrier Procedure (ODB)

The ODB frontal crash test was developed from 1989-1995 [EEVC 2013], and it simulates the collision of the tested vehicle against another vehicle of similar mass. The main characteristic is the use of a deformable barrier, which was developed by the European Enhanced Vehicle Safety Committee (EEVC) [EEVC 2013]. The test consists of a frontal crash where the car impacts the barrier with an off-set of 40 percent, on the driver side. This is the current procedure used by the European regulation and directive where the test speed is 56 km/h. From 1996, Euro NCAP [Euro NCAP 2013] adopted this procedure to the European consumer information program, in the Euro NCAP test the speed is increased to 64 km/h.

The EEVC barrier is a calibrated kinetic energy absorber developed to be used for full scale crash testing in automotive passive safety and crashworthiness field. This barrier is based on the original work of EEVC Working Group 11. Based on aluminium honeycomb technology, this barrier is particularly used by car manufacturers and test laboratories worldwide for the assessment of motor vehicle passenger's protection in case of frontal off-set collision according to following standards:

- UN ECE R94, European Directive 96/79/CE, FMVSS 208, ARD 73/00
- Euro NCAP, IIHS, C-NCAP, ANCAP, J-NCAP etc…

In the off-set frontal crash test, the vehicle initially contacts the deformable aluminium barrier at the impact speed defined regarding protocols requirements. A Hybrid III (HIII) ATD is used to evaluate the self-protection of the vehicle is assessed through the dummy injury values. The HIII measures the likeliness of injuries in this type of crash.

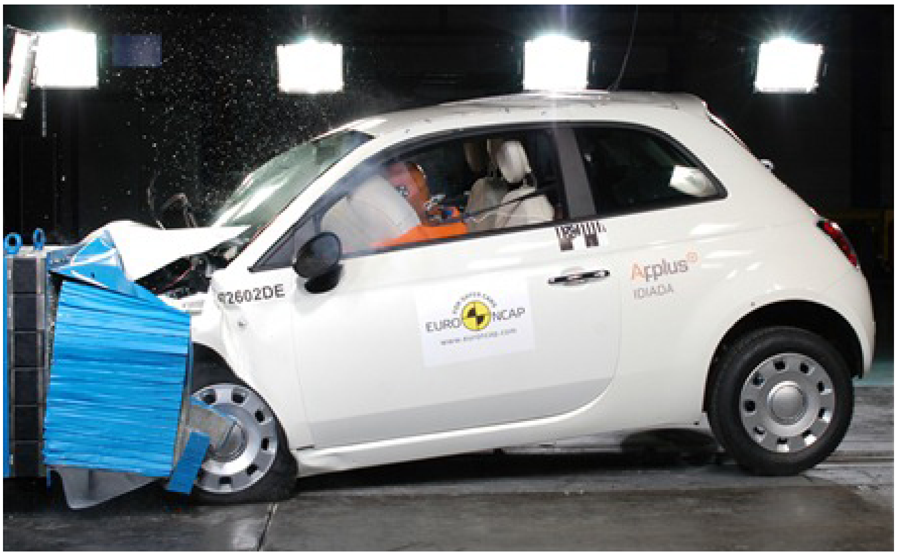


Figure 2.1: Euro NCAP ODB crash test.

2.1.2 Progressive Deformable Barrier Procedure (PDB)

The off-set test using the PDB is a 60 km/h and 50 percent overlap (on the driver side) test that simulates a frontal collision of the tested vehicle against an average modern car. The details of the test procedure are described in the [ECE 2007].

The PDB stiffness is in line with the current European vehicle fleet. When comparing the force deflection curve of 26 cars tested according to Euro NCAP protocol with the PDB certification corridor (note the corridor is shifted in order to account for the assumption that the first 500 mm of the crash in Euro NCAP are purely caused by the deformation of the barrier face) a good correlation can be demonstrated, see Figure 2.2

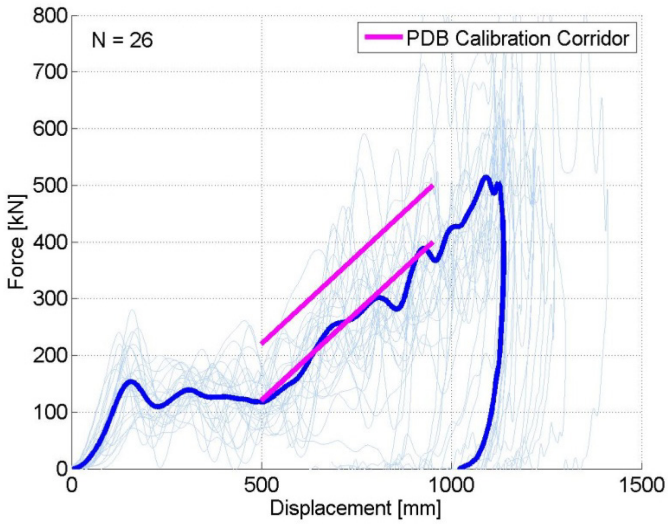


Figure 2.2 Average force-deflection curve of 26 cars tested within Euro NCAP from 2006 to 2009 together with the shifted PDB calibration corridor.

The PDB is significantly stiffer than the ODB [Delannoy 2005] and has been proposed by France in previous European research projects. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The PDB is a calibrated kinetic energy absorber developed to be used for full scale crash testing in automotive passive safety and crashworthiness field. This barrier is based on national research work in France. Based on aluminium honeycomb technology, this barrier has the ability to assess the tested vehicle aggressiveness.

Figure 2.3: PDB 60 km/h crash test.

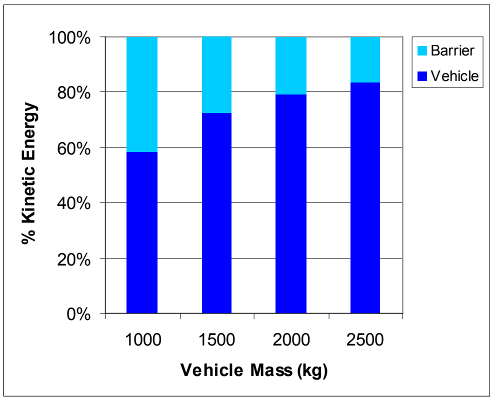
2.1.3 Narrow off-set procedure

The narrow off-set test is a frontal impact against a rigid obstacle with an overlap smaller than 30 percent, on the driver side. Recent research programs conducted by IIHS identified that a number of accidents are still source of severe injuries to the occupants. A narrow object (e.g. trees, lamp post) is one of these configurations. IIHS has been working for this research in order to determine what kind of additional tests should be added to its crashworthiness evaluation program. IIHS has been conducting a series of frontal pole impact tests to determine whether to add this test configuration to their US consumer information program. Now they added an off-set frontal impact at 64 km/h with 25 percent overlap against rigid barrier whose corner is pole shape [IIHS 2012] into their current program to address these injuries. This configuration leads to higher intrusions (compared to the larger overlap). A HIII dummy will be used in the driver side to measure the likeliness of injuries in this type of crash.

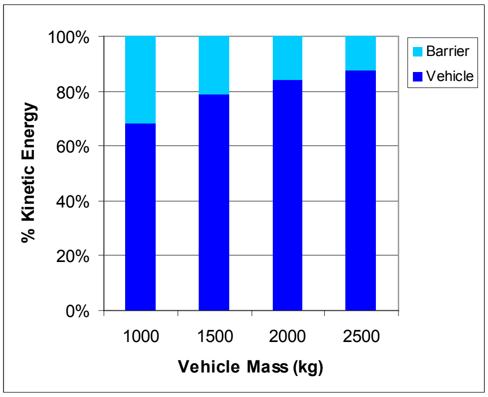
2.2 Proposed test configuration for assessing compatibility

Previous compatibility research projects identified frontal crash incompatibilities between vehicles, in principal due to the difference in front stiffness, bad structural interaction, insufficient compartment strength and mass difference. Today's self-protection requirement leads to design of large vehicles with a stiffer front end (compared to small vehicles) in order to compensate for their mass. The current frontal ODB test is more severe for heavy vehicles than lighter vehicles. Due to this self-protection trend, compatibility requirements are more and more difficult to achieve. However, the FIMCAR accident analysis showed that with new cars poor structural interaction, compartment strength (especially in accidents with HGV and objects) and high acceleration loading to the occupant seem to be more important [Thompson 2013 / Section II].

The test severity was defined in previous research projects using the EES (energy equivalent speed). Figure 2.4 shows the test severity trend in the ODB tests.



R94



Euro NCAP

Figure 2.4: Estimation of test severity, % of kinetic energy absorbed.

In Figure 2.4, the energy absorbed by the deformable barrier was estimated to be 50 kJ independent of vehicle mass and dimensions (see below). Furthermore kinetic energy after the impact was neglected.

The EES definition is currently used to estimate the test severity, EES formula is shown in Equation 2.1.

$$EES[m/s] = \sqrt{v[m/s]^2 - \frac{2 \times E_{ODB}[J]}{m[kg]}}$$

Equation 2.1: EES formula.

The energy absorbed by the barrier was obtained from a total of 17 Euro NCAP tests that were analysed in WP2, data from LCW was used to estimate the energy absorbed by the deformable element. From this study, 53.81 kJ represents the average of the energy absorbed by the barrier, which has been measured using load cell wall data of different family of vehicles. All cases assume that the deformation of the barrier occurs prior to the deformation of the vehicle. In the R94 test, the energy absorbed by the barrier can be also estimated in 50 kJ as it uses the same barrier and the barrier is bottomed out in the tests.

It is required to maintain current compartment strength, to improve front structural interaction and to limit vehicle front-end aggressiveness. In other words, it is necessary to assess the possibility to check and improve partner-protection while keeping the current level of self-protection.

The current ODB test was developed fifteen years ago and adapted to car designs (geometry and force deformation) from the 90's. Since then, introduction of regulation, ratings, insurance test and recently pedestrian tests have modified a lot of car front designs in terms of stiffness and geometry to achieve these requirements.

With the self-protection requirements for the ODB test, regulations and ratings, all cars offer equivalent behaviour against a fixed obstacle. These tests lead to stiffer front-end and higher compartment strength. Solutions have been optimised against the ODB test or the rigid wall but not in car-to-car configurations.

The proposed new procedure should not compromise or decrease the current self-protection level. That is why the proposed procedure checks compartment strength and structural interaction at the same time. The main objective is to assess compatibility issues identified in the accident research analysis (WP1) and decrease the injury risks in real world accidents.

Therefore, the vehicles need to improve partner-protection (structural interaction, front-end forces, etc.), and should maintain the current level of self-protection (compartment strength, dummy injury).

Figure 2.5 highlights heterogeneity in partner-protection caused by vehicles designed according today's regulation. Severity rate for self and partner-protection are calculated as noted in equation of Figure 2.5. Note that Figure 2.5 is an analysis of vehicle to vehicle frontal crashes.

$$SR(\text{protection}) = \frac{(\text{Fatalities} + \text{Severe\_injuries})_{int}}{(\text{Fatalities} + \text{Severe\_inj} + \text{Slight\_inj} + \text{Not\_inj})_{int}}$$

$$SR(\text{partner}) = \frac{(\text{Fatalities} + \text{Severe\_injuries})_{ext}}{(\text{Fatalities} + \text{Severe\_inj} + \text{Slight\_inj} + \text{Not\_inj})_{ext}}$$

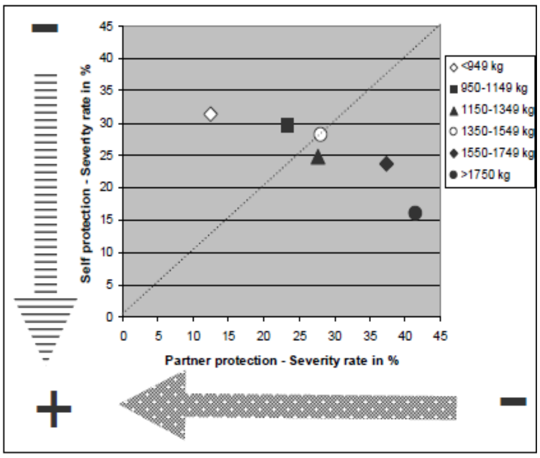


Figure 2.5: Severity rates in different vehicles [Chauvel 2011].

The line on the Figure 2.5 represents cases for which self-protection and partner-protection are identical. Vehicles ranging from 950 to 1549 kg are relatively close to this configuration. The heaviest vehicles (above 1550 kg) show high level of crashworthiness and weak performance regarding partner-protection, whereas vehicles under 950 kg present a smaller self-protection level associated with a small percentage of casualties in the opposite car [Chauvel 2011].

The off-set test configuration proposed to evaluate compatibility is the PDB procedure described in [ECE 2007, Delannoy 2007]. The 50 percent overlap and the 60 km/h speed ensure a high deceleration test pulse and a similar loading of the passenger compartment (compared to R94).

On the other hand, the 50 percent overlap and 150 mm ground clearance of PDB procedure ensure that the all relevant front parts of the vehicle are in direct contact with the barrier when tested in off-set conditions. An overview of test data collected in the previous research project VC-Compat is given in [Davies 2006]. Figure 2.6 shows a summary of the structural database results of VC-Compat.

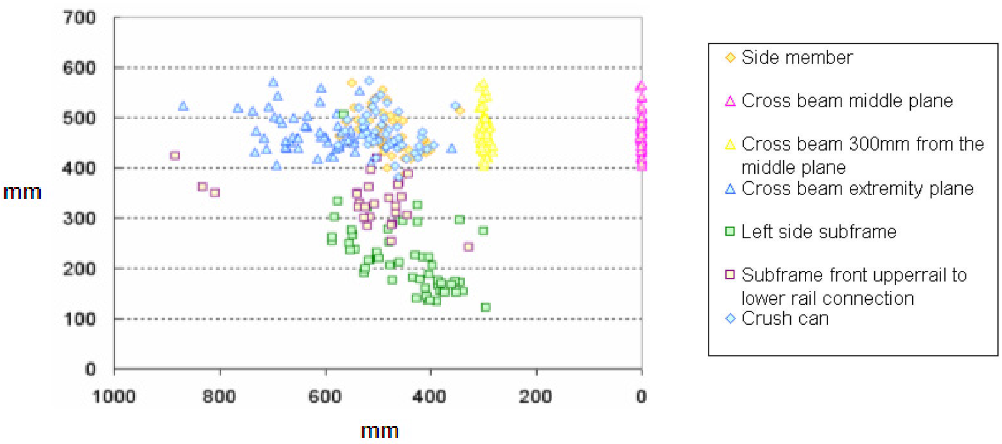


Figure 2.6: Vehicle structural database.

2.2.1 Justification of proposed barrier face (PDB)

The following list of issues of the current ODB barrier was provided by EEVC WG15 [ECE 2007]:

- Barrier instability for new generation of car, stiffness of barrier too low for modern vehicles.
- Test severity increases with car mass and constant test speed
- Self-protection level depends on the vehicle size and mass.
- Difficult to assess force levels with this barrier type and configuration with constant test speed (bottoming out of barrier causes undesired inertial loads for measurement of a car's frontal force).
- No assessment of structural interaction is possible because of load spreading in the barrier and subsequent barrier bottoming out.

The PDB stiffness increases with crush depth and also provides different force deflection characteristics in the upper and lower sections of the barrier (Figure 2.7). The PDB was designed to harmonise the test severity among vehicles of different masses. The PDB will encourage light vehicles to maintain the current passenger compartment stiffness without increasing the front-end force levels of heavy vehicles (Figure 3.3). This will lead to a better force matching between vehicles, one of the objectives towards compatibility.

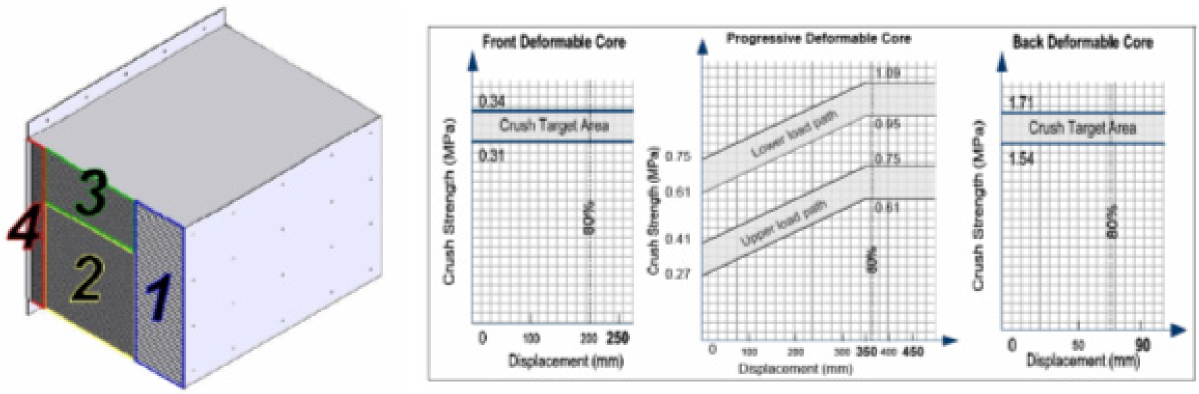


Figure 2.7: PDB characteristics [according to Delannoy 2005].

The PDB represents a significantly stiffer barrier compared to the ODB (current barrier) [Delannoy 2005]; Figure 2.8 shows a comparison between both barriers in terms of global force and energy.

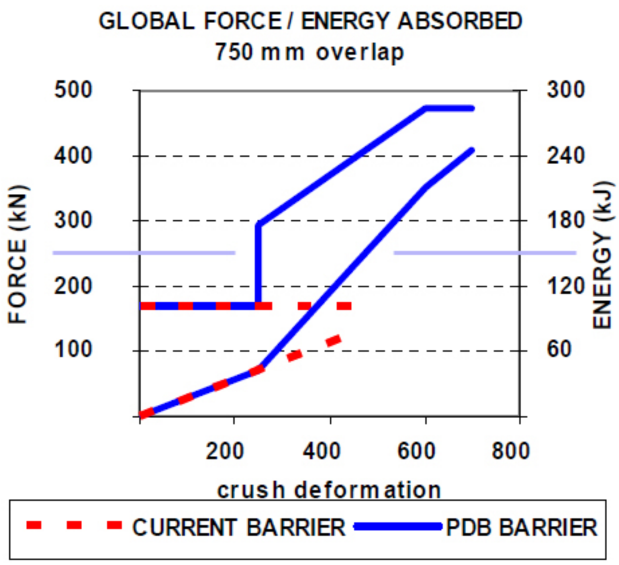


Figure 2.8: PDB vs. ODB [Delannoy 2005].

Furthermore, the dimensions and stiffness of the PDB make the bottoming-out phenomenon very unlikely. The barrier face is capable of generating sufficient differential deformation of the weak and stiff parts of the car's front structure to replicate what happens in most accidents. This will encourage future car designs to incorporate structures, which distribute the force on a large surface better for structural interaction and partner-protection.

The 60 km/h test speed with PDB will increase the test severity for light vehicles which will lead to an increase of the front structure stiffness. The severity for heavy vehicles is expected to be unchanged, so the frontal stiffness of heavy vehicles should not change. As conclusion, test severity for all vehicle mass range will be harmonised.

The PDB test procedure puts under control the energy absorbed by vehicle, the barrier is supposed to represent the opponent vehicle that should also be protected, it does not bottom-out and its deformations can be further analysed.

In the current off-set test procedures (ODB), the car impacts against a weak deformable obstacle (with barrier bottoming-out phenomenon even seen in tests with light stiff vehicles), so the barrier deformation cannot be analysed.

FIMCAR accident analysis results show a significant number of structural interaction issues, in which the load paths involved in the crash are not working in the same way as in a test performed in a laboratory. Although a car impact against a rigid wall might be simpler it does not represent the most common pulse observed in the real world accident (this effects for example crash structure behaviour and airbag firing time).

3 ASSESSMENT CRITERIA DEVELOPMENT AND VALIDATION

3.1 Analysing input of WP1 (accident data) and WP6 (assessment methods) about off-set procedure

3.1.1 General FIMCAR Strategy

Early activities in FIMCAR focused on the compatibility characteristics to be addressed and their priorities. It was important to divide the issues into as many topics as possible to ensure that the test candidates could address specific issues. The resulting overview of frontal impact and compatibility issues presented and discussed in FIMCAR is shown in Figure 2.8. From this organisational description, the issues for FIMCAR could be discussed within the group to establish a common understanding.

During FIMCAR Task 6.2, the candidate test procedures under development in WP2, 3 and 4 were monitored to identify if there was any risk that a compatibility characteristic would not be addressed in the final deliverables of FIMCAR. Through this preliminary evaluation process, the consortium came to a common agreement that FIMCAR should develop both a full width and an off-set test procedure to address all safety issues in frontal impact. This resolution was finalised in the General Assembly meeting in October 2010 and presented to the GRSP Informal Group on Frontal Impact.

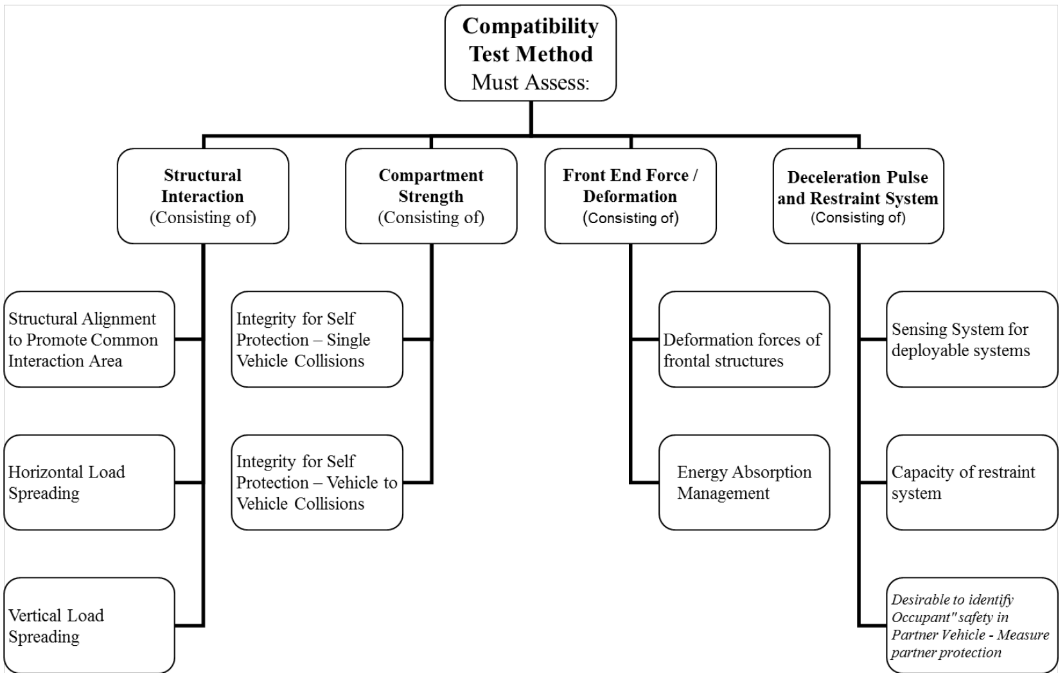


Figure 3.1: Compatibility characteristics [Thomson 2013 / Section XI].

Task 6.1 monitored the activities in WP1 as well as the external activities. An output of these activities is a final set of priorities for the frontal impact issues outlined in the previous figure. The FIMCAR consortium identified key issues that must be resolved within FIMCAR (Priority 1) and issues that should be addressed but are not critical to be finalised within FIMCAR. The results of this prioritisation process are shown in Figure 3.2.

	Assessment requirements							
	Structural Interaction		Front End Force / Deformation (Consisting of)		Compartment integrity		Restraint system	
	Alignment	Load Spreading (Load paths / connections)	Deformation forces of frontal structures	Energy Absorption Management	Sufficient for single vehicle accident	Enhanced for light vehicles in vehicle to vehicle accident	(Assess over range of pulses)	Test Restraint Capacity
Priorities For FIMCAR	1	1	2	1	1	2	1	1

Figure 3.2: Priorities rating of FIMCAR research issues [Thomson 2013 / Section XI].

The main features to note in the FIMCAR priorities are that the structural issues related to small vehicles have a lower priority. This is a result of the data from WP1 as well as some of the recent data from GRSP IG FI. Smaller vehicles are known to have higher injury risks in car-to-car impacts. Historically the issues were largely attributed to the weaker structures (compartment and frontal crashworthiness) in small vehicles compared to heavier vehicles, resulting in excessive deformation of small vehicles. Recent data now shows that the excessive deformation of small vehicle compartments (intrusion) is not overrepresented in accident data. The main issue with small vehicle safety appears to be high velocity changes for low mass vehicles and resulting acceleration related injuries to the occupants. The mass induced delta-v differences are not easily resolved in a fixed barrier regulation procedure.

3.1.2 Contribution of Off-set Test Procedure to Frontal Impact

There are 8 main priorities identified for frontal impact protection, see Figure 3.2. Not all these priorities are necessarily needed to be evaluated in an off-set procedure if it is combined with the full width test in a common frontal impact protection assessment. The main issues that are expected to be evaluated in an off-set procedure are the load spreading issues (Structural Interaction) and single vehicle collision compartment strength evaluation. In addition, the combination of a full width and off-set test provide a possibility to evaluate the restraint system for different pulses.

The off-set test has the potential to assist in evaluating structural alignment and deformation forces of frontal structures. As structural alignment is desirable in the initial crash stages, the full width test is the main candidate since it can continuously measure contact forces during the crash while the PDB only provides the final deformed shape of the barrier at the end of crash. The deformation forces of the front structures can be indirectly evaluated by the PDB barrier deformations. Although this is desirable for assessing force level matching between vehicles, the accident data in WP1 did not indicate that this issue was a high priority for current FIMCAR activities.

There were some critical structural interaction issues that were identified in the accident analysis in FIMCAR. The results in the FIMCAR Deliverable D1.1 [Thompson 2013] (see Section II) indicated that “over-ride/under-ride”, small overlap, and fork effect were predominant in the cases with injuries and fatalities. These characteristics were observed in both vehicle-to-vehicle and vehicle-to-object collisions. These issues can be considered the main issues to be addressed in an off-set test procedure where the PDB provides the possibility to evaluate all these points.

The collisions with over-ride/under-ride are proposed to be resolved if vehicles have good structural alignment and vertical load spreading. It is therefore critical that an off-set test procedure can assess how well a vehicle distributes the loads from the proposed interaction zone, 406-508 mm, and the area above and below this area. Currently in FIMCAR the emphasis is to assess loads below the bumper and identify a need to assess loads above the bumper.

Both the small overlap and fork effect issues are related to the horizontal load spreading issue. Small overlap is related to how wide the vehicle can distribute crash loads in the outer extremity of the vehicle, essentially outboard of the main longitudinals. The fork effect is related to the front bumper cross beam strength, particularly between the main longitudinals.

Load spreading can be measured both with a full width load cell wall or an off-set test procedure. Previous [Davies 2006] and current research indicate that the best representation of car-to-car impacts is with a larger deformable barrier that introduces vertical and lateral shear within the vehicle's front structures. It is preferable if the barrier does not bottom out so that extreme deformations are introduced. A PDB approach can be an effective method for assessing load spreading.

3.1.3 Test Severity

The final test severity of the FIMCAR frontal impact assessment has not been finalised at the time of publication of this report. There are different strategies that can be considered. The most likely scenario for FIMCAR is that the full width test is used to assess the restraint system response and address the main injuries observed in the thorax. An off-set test would complement this evaluation by assessing the severe and fatal injury risks in frontal crashes. The current frontal impact regulation is based on the fatality risk in a 50% off-set, 50 km/h (for each vehicle), car-to-car impact. Further work with the accident statistics is needed to confirm these numbers but the current PDB test speed of 60 km/h appears to provide this severity level for most of the vehicles [Delannoy 2005]. Any increases in the desired protection level of an off-set test condition would require a review of the PDB test speed.

3.2 Review and Analysis of Test Data Available from Past Compatibility Research

Being the reference test procedure for crashworthiness in Europe, there is a huge amount of data for off-set test procedures. FIMCAR has been analysing the most relevant available data in some of these procedures such as Euro NCAP, PDB and R94 test data. Each pack of data has been used for a particular objective, e.g. test severity check (R94), assessment criteria development (PDB).

Below the list of data packs used in the off-set procedure:

- PDB tests at 60 km/h, total of 37 tests from previous research projects
- Euro NCAP test (total of 18) from FIMCAR partners testing for Euro NCAP
- ECE R94 tests from FIMCAR partners car makers (only used for reference)

3.3 Development of Assessment Procedure

The main objectives of the off-set test procedure are to address:

- Compartment strength
- Structural alignment
- Load spreading issues

- Restraint system issues (different test pulses).

The current ODB (ECE R94) test and the PDB (Progressive Deformable Barrier) procedure as proposed by France in previous projects were the main candidates. Previous research indicated that load cell measurements in off-set tests do not result in appropriate assessment of the load distribution (due to load spreading in the deformable barrier face load cell wall data is misleading) [Delannoy 2003].

Following that the first FIMCAR decision was taken to concentrate on the PDB procedure and to assess barrier face deformation, assessing the barrier face deformation is impossible with the current ODB barrier face because it is normally over crushed and the vehicle contacts the rigid barrier face.

3.3.1 ODB

The test severity in the current ODB test procedures, R94 and Euro NCAP, can be measured by the vehicle pulse and the dummy readings. Another methodology to measure the test severity is using the EES, Figure 2.4, which varies in function of the vehicle mass.

The Euro NCAP dataset available at FIMCAR has been used to establish the test severity for the ODB tests. This test severity has been estimated as explained in Section 2.2 of this report, the average of EES from a total of 17 Euro NCAP test has been estimated in 57 km/h, with values between 50.9 and 60.1 km/h.

A way to represent the EES against vehicle mass can be found in Figure 3.2, in this diagram the level of test severity for the R94 has been compared with the estimated EES for some PDB tests.

The assessment criteria for the ODB test procedures only consider self-protection issues. In case of R94, the parameters are focused on HIII dummy reading and risk of injury. Details are explained in [EEVC 2013]. Moreover, in the case of Euro NCAP configuration, the self-protection is evaluated not only by dummy parameters and risk of injury, but also by the passenger compartment assessment, details can be found in [Euro NCAP 2013]. It is worth to mention that in the Euro NCAP methodology, the passenger compartment parameters are evaluated following both subjective and objective criteria.

3.3.2 PDB

The test severity needs to be defined taking into account sufficient compartment strength requirements. A way to assess test severity is to use the vehicle deformation energy expressed by EES, as described in Equation 2.1. The proposed test procedure shall ensure a level of EES comparable to the today's EES level (observed in ECE R94 test conditions), for that reason the PDB test speed is fixed at 60 km/h. The details of the test procedure are described in [Delannoy 2007].

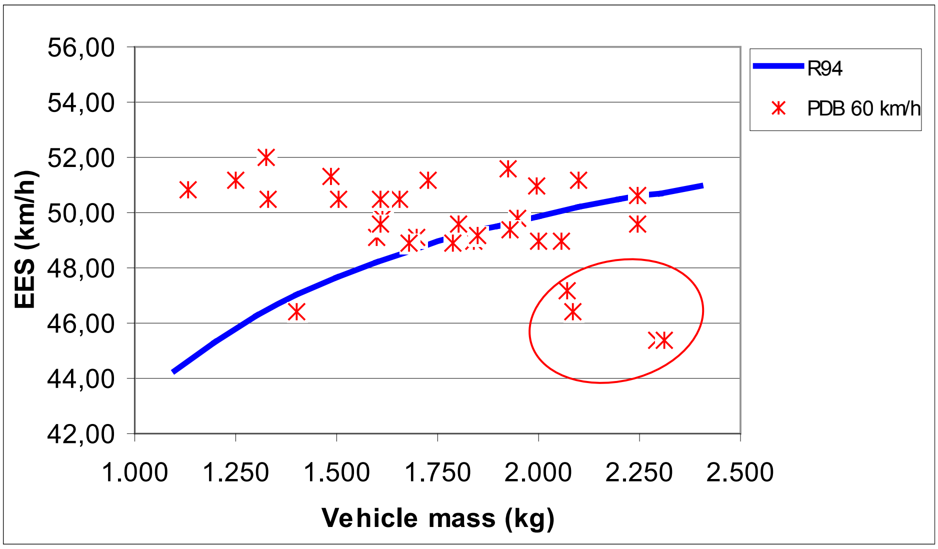


Figure 3.3: EES of PDB 60 km/h database.

The EES of the PDB tests has been calculated using Equation 2.1, where the energy absorbed by the barrier is a variable value and it is obtained from the deformation of the barrier [Delannoy 2007].

According to the database in few cases (red circle in Figure 3.3) the EES of the PDB60 test was reduced by about 5 to 10% compared to the EES of R94 test. The reduced EES is observed in vehicles with a mass between 2070 to 2310 kg, vehicles which are able to deform the barrier in a significant manner. The characteristics of these vehicles would allow them to reduce the front-end unit stiffness and as consequence deform less the barrier maintaining the current R94 level of vehicle deformation and passenger compartment loading. In other words, for future generation of vehicles the test procedure would provide the possibility to balance the barrier and vehicle deformations, which in some cases will mean reducing the stiffness of the front-end structure, giving the possibility to reduce the vehicle weight.

For most of the vehicle types, the PDB is not expected to reduce the passenger compartment stiffness. Reducing the passenger compartment stiffness would compromise the vehicle self-protection.

In the PDB test it is proposed to use a self-protection evaluation as it is used in current ODB test procedures. HIII dummies will be used in driver and front passenger position to evaluate the self-protection of the tested vehicle, equivalent methodologies for dummy evaluation as described in [EEVC 2013] and [Euro NCAP 2013]. In addition, it is proposed to use passenger compartment evaluations similar to the one described in the Euro NCAP protocol, the proposed methodology will include only objective evaluations of the passenger compartment such A-pillar and steering column displacements.

This 50 percent overlap off-set test will assess self-protection issues using dummy values and passenger compartment results and partner-protection issues using measurements from a PDB barrier after the test. This barrier is currently only used in research applications and is not part of a regulation or consumer test procedure.

The 50 percent overlap and the barrier characteristics allow the PDB to identity the main structures involved in the frontal crash. Geometrical data from previous European research projects indicated that the main structures of the vehicles will interact with the PDB. Figure 3.4 shows the interaction areas for the front-end structures (PEAS and SEAS) in both, R94 and PDB barriers.

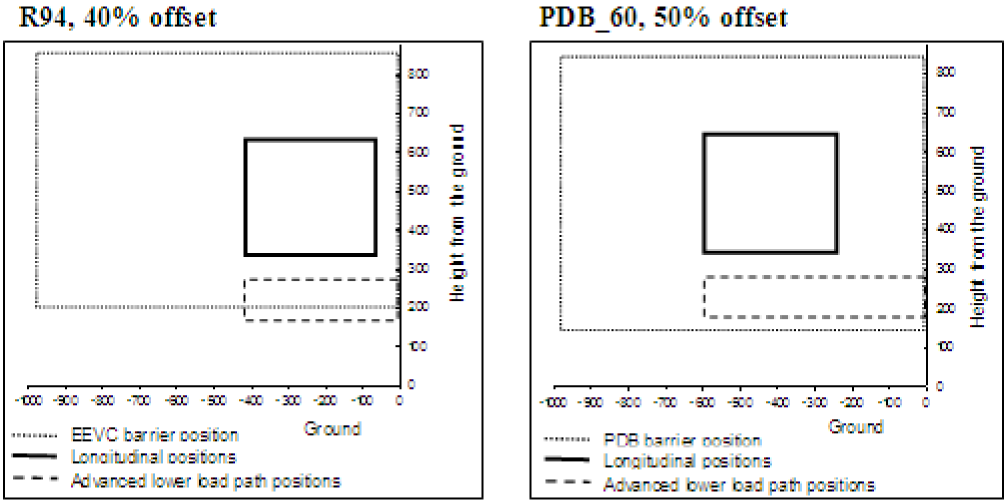


Figure 3.4: Barriers and structure location [Davies 2006].

The barrier stiffness increases with depth and has upper and lower load levels to represent an actual car structure. The progressive stiffness of the barrier has been designed so that the Equivalent Energy Speed (EES) for the vehicle should be independent of the vehicle's mass.

The use of a PDB barrier should thus harmonise the test severity among vehicles of different masses by encouraging lighter vehicles to be stronger without increasing the force levels of large vehicles.

The key data used for compatibility in a PDB test is the post-crash deformations of the barrier. A 3D image, Figure 3.5, of the barrier is recorded in the computer and the depth and distribution of the deformations are used to assess the vehicle's compatibility characteristics.

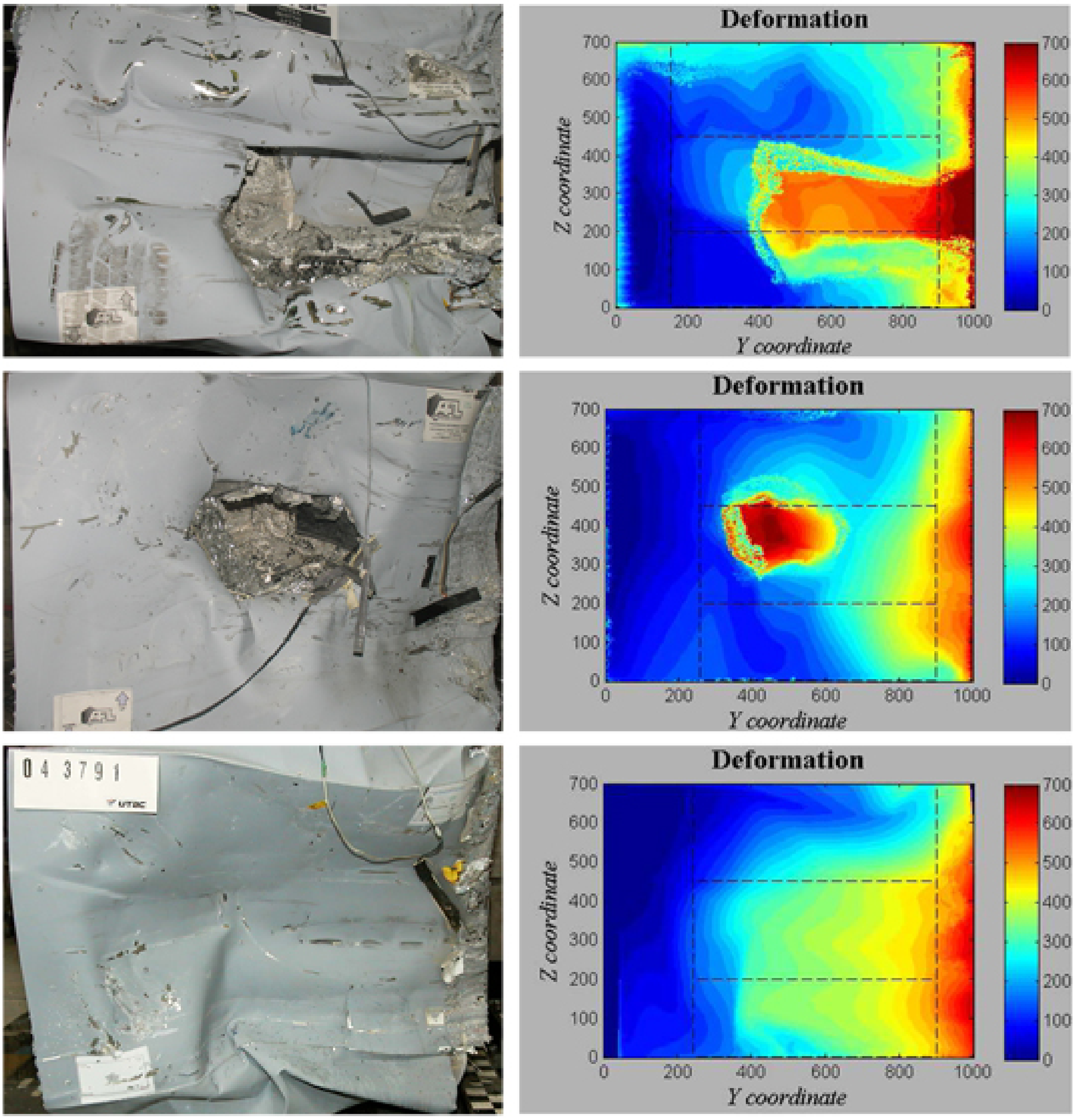


Figure 3.5: Example of PDB digitalisation.

The upper image of Figure 3.5 shows a barrier deformation of a stiff crossbeam but vertical load spreading could be improved, middle image shows poor load spreading, the longitudinal punched a hole into the barrier, lower image shows relatively good vertical and horizontal load spreading.

Metrics assessing the depth and distribution of the barrier deflections are under development in FIMCAR. Instrumented HIII dummies, as in current ODB test procedures, are used to assess the risk of injuries for the occupants.

The barrier will be divided in vertical zones, as shown in Figure 3.6, each area with a defined objective for evaluation. The precise location of the areas is still in discussion.

- **Upper Area** [e.g. from 820 to 600 mm to the ground]: For most of the vehicles this area is above the PEAS and SEAS structures. Significant longitudinal deformations in this area would induce a risk of under/overriding issues (i.e. risk for non-compatible situations in front-side collisions).

- **Middle Area** [e.g. from 600 to 350 mm to the ground]: Area including the CIZ (common interaction zone). For most of the vehicles this is the area where the PEAS are located. Deformations of the barrier will be required in this zone to promote the structural interaction between vehicles in case of frontal collision. On the other hand, the homogeneous deformations of the area will be promoted to encourage the improvement of different partner-protection issues like "fork-effect" or the "small overlap"
- **Lower Area** [e.g. from 350 to 180 mm to the ground]: For most of the vehicles this area is below the PEAS, in some cases the SEAS are located in this area. Deformations in the area will be promoted in order to promote compatibility issues. The homogeneous deformations of the zone will be as well promoted.

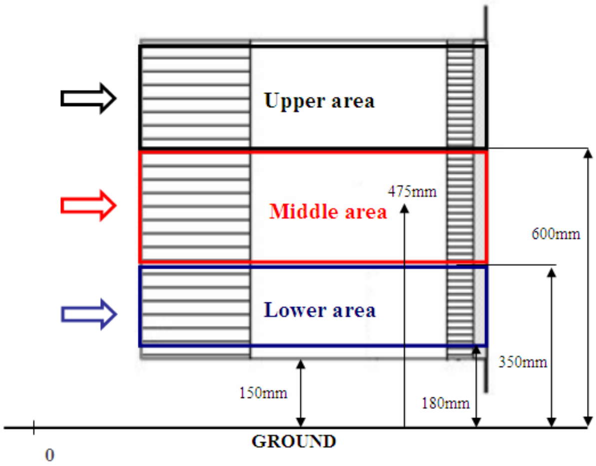


Figure 3.6: Areas of assessment.

The analysis within each zone does not consider the total width of the barrier; the extremities of the barrier are excluded. The zone width covers 150 mm from the barrier edge to a distance equal to the half of the vehicle width minus 100 mm, the horizontal limits are shown in Figure 3.7.

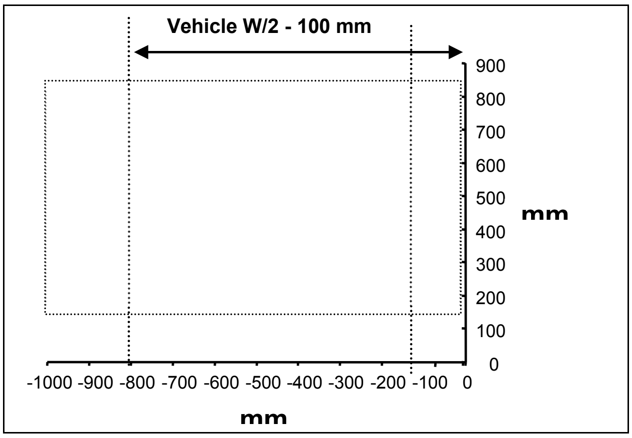
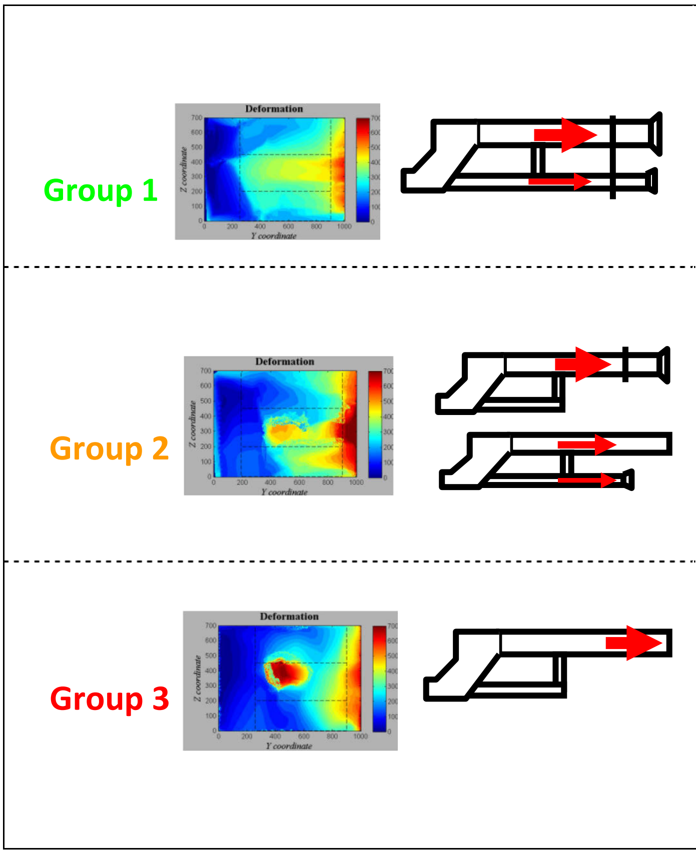


Figure 3.8: Lateral limits.

The zones defined ensure the evaluation of the front structure over a wide range, taking into account compatibility issues identified in FIMCAR WP1 such as fork-effect, small overlap or under riding but excludes the area of large deformation due to vehicle rotation and engine dump at the centre of the vehicle. The following two criteria are obtained from the barrier digitalisation. These parameters will be used to evaluate the partner-protection of the vehicle.

By dividing the barrier in zones, the assessment procedure will be developed focusing each zone to a particular compatibility issue and defining the appropriate criteria to assess this compatibility topic.

The off-set test assessment procedure was supported by a database of 37 PDB tests at 60 km/h. The barrier deformations of these tests were analysed and taken as a reference for further metric investigations. The database is the result of previous research projects, e.g. VC-Compat. In a first stage, the barriers were classified following a subjective approach, gathering the barriers that suggest a good performance in compatibility in a first group (G1), the barriers that suggested a bad compatibility performance in a separate group (G3) and finally the barriers between G1 and G3 were classified in G2, Figure 3.9. Vehicle data (e.g. mass, model, etc.) was not taken into account for the subjective classification, only barrier deformation was considered.



Group 1:
- ⇨ PEAS including stiff cross-member, SEAS that contribute to the deformation of the barrier. Good connections between PEAS and SEAS which suggests a proper engagement with the partner vehicle.
- ⇨ Barrier that suggests good performance in compatibility.

Group 2:
- ⇨ PEAS including stiff cross-member, no significant contribution of the SEAS in the deformation of the barrier. Marginal connections between PEAS and SEAS.
- ⇨ PEAS with weak cross-member, partial contribution of the SEAS to the deformation of the barrier. Marginal connection between PEAS and SEAS.

Group 3:
- ⇨ PEAS with weak cross-member, no significant contribution of the SEAS to the deformation of the barrier. Marginal connections between PEAS and SEAS.
- ⇨ Barrier that suggests poor performance in compatibility.

Figure 3.9: Subjective classification by groups

In a second stage, the barriers in each group (G1, G2 and G3) were classified from best to worst performance also using subjective criteria, see Figure 3.10.

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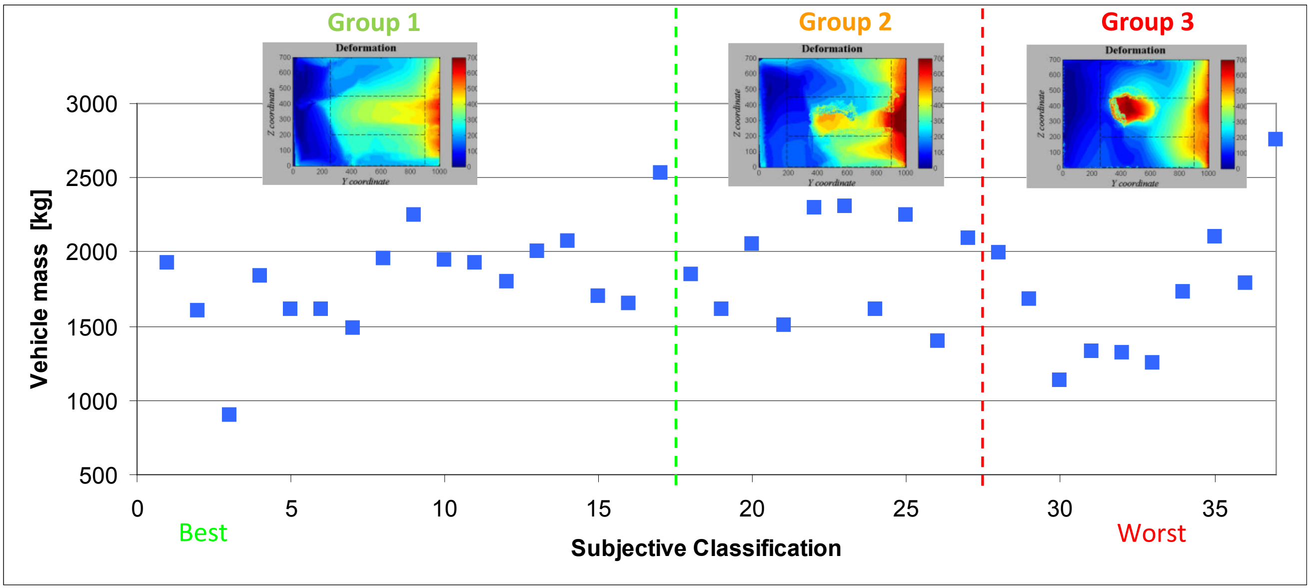


Figure 3.10: Subjective classification from best to worst.

The subjective classification described above was agreed among WP2 partners and used as guidance for an initial stage of the development of the metric, a good correlation between the subjective classification and the initial proposals for metric (objective method) gave a good starting point for the development of the metric.

3.4 Development of Assessment Criteria and Metric

In order to assess compatibility using the PDB 3D image, two different criteria were developed. The criteria are assessing the barrier deformation in all three axes, the **detection of load paths,** which focus on the assessment of the deformation in the longitudinal axis, while the **load spreading** criteria assess the characteristics of the deformations in the horizontal and vertical axes, see Figure 3.11.

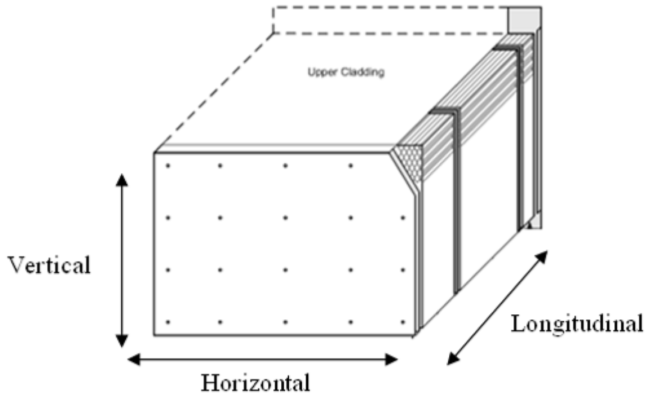


Figure 3.11: PDB barrier axis.

3.4.1 Draft Metric

The objective of the metric is to discriminate good and bad performance in compatibility.

In an initial phase of the development of the metric, a single score (*S*) approach was developed. The score being the result of a formula which combines the longitudinal deformation and load spreading criteria for the lower, middle and upper areas, S_i, where $i=U, M$ and L.

As shown in Equation 3.1, the result will take into account the load paths detection criteria, *d*, and the load spreading criteria, *H*, for the Upper, Middle and Lower area of the barrier.

$$\boxed{S = f(S_U, S_M, S_L)} \qquad \boxed{S_i = f(d_i, H_i)}$$

Equation 3.1: Scoring formula.

The score, including "weighting factors" for the different sub-scores, can be developed following the priorities to evaluate the frontal compatibility.

Several metrics were investigated in WP2. Figure 3.12 shows an example of correlation between subjective (as explained in Section 3.3.2 of this report) and objective classification using the TV criteria (see Chapter 3.4.4) for assessing the load spreading. A reasonable good correlation can be observed. However, some discrepancies were found, those are mainly due to the effect of sharp edges and boundaries of assessment areas on the TV criteria.

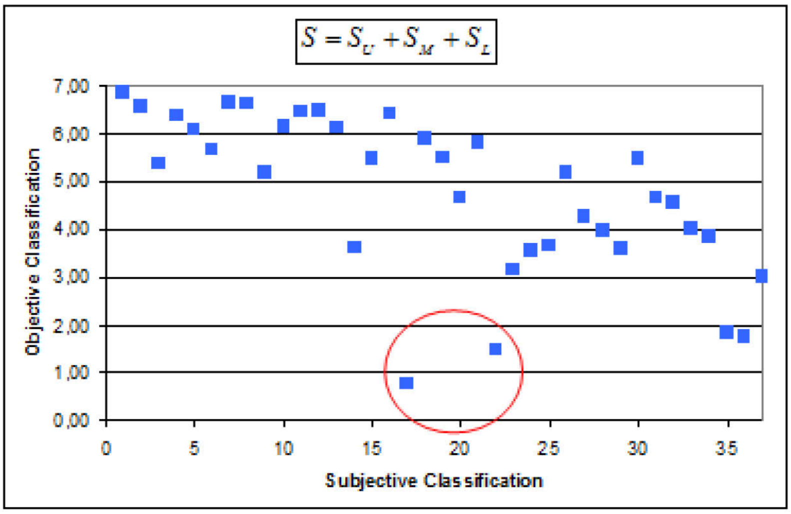
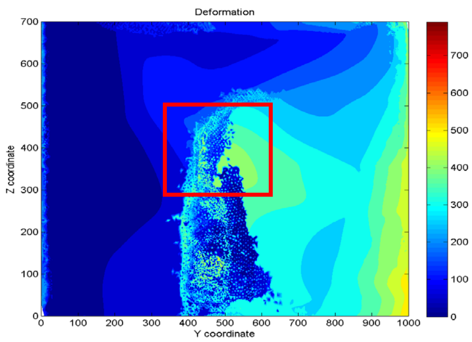
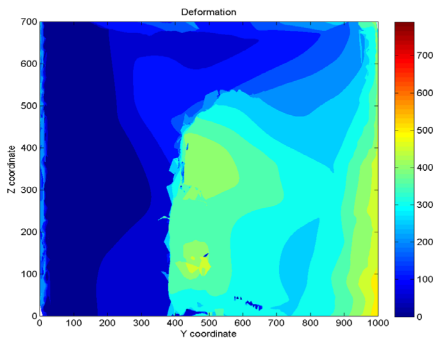


Figure 3.12: Subjective vs. objective classification.

As shown in Figure 3.13 the TV criterion is very sensitive to sharp edges. The left picture of Figure 3.13 shows the image and TV value before post-processing of the image. After post-processing, right picture, the TV value is about 50% lower (note: the lower the TV value is the better is the rating).



TV for middle area 3871



TV for middle area 1430

Figure 3.13: Post-processing PDB scan.

So it is recommended to post-process the PDB scan in order to remove measurement/scanning issues before analysing any assessment criteria.

3.4.2 Strategy for Metric Development

In second phase and following the priorities established from the FIMCAR consortium the metric was re-issued, the metric was focusing on the main objectives defined by the group. These priorities are summarised in the following key issues:

- Relevant crash loads to be in the common interaction zone (406 to 508 mm). Loads should be distributed horizontally across the common interaction zone
- Vertical load distribution will be assessed inside and below the interaction zone.

3.4.2.1 Relevant Crash Loads to be in the Common Interaction Zone (406 to 508 mm). Loads Should be Distributed Horizontally Across the Common Interaction Zone

In the PDB assessment procedure this requirement should be reflected in the criteria assessing the deformations of the barrier at the middle area.

According to that point, the longitudinal deformation will be used to assess if the PEAS are able to deform the barrier in a sufficient manner, but not limiting its maximum deformation.

In other words, a limit for minimum deformation could be established, while no limits of maximum deformations will be further investigated.

The longitudinal deformation criteria should provide an estimation of the amount of load in the area and the load spreading criteria its horizontal load distribution. This analysis will give an estimation of potential risk for compatibility issues like “small overlap” or “fork effect”.

3.4.2.2 Vertical Load Distribution will be Assessed Inside and Below the Interaction Zone

The criteria obtained at the lower area should answer this requirement. The longitudinal deformations will provide an idea about the loads in the area below the interaction zone. The metric should promote the presence of lower load paths (SEAS), in particular for vehicles involving a crash test with a large kinetic energy.

In the case that SEAS will be detected, then the load spreading criterion at the lower area will also contribute in the metric.

Finally, the upper area will contribute also to the metric. Vehicles without load paths in the common interaction zone, but with excessive high PEAS, which are above the zone will be penalised.

In these cases, the longitudinal deformation criteria in the area above the common interaction zone will give an estimation of potential risk of “overriding” issues.

The proposed metric will be based on a PASS/FAIL approach.

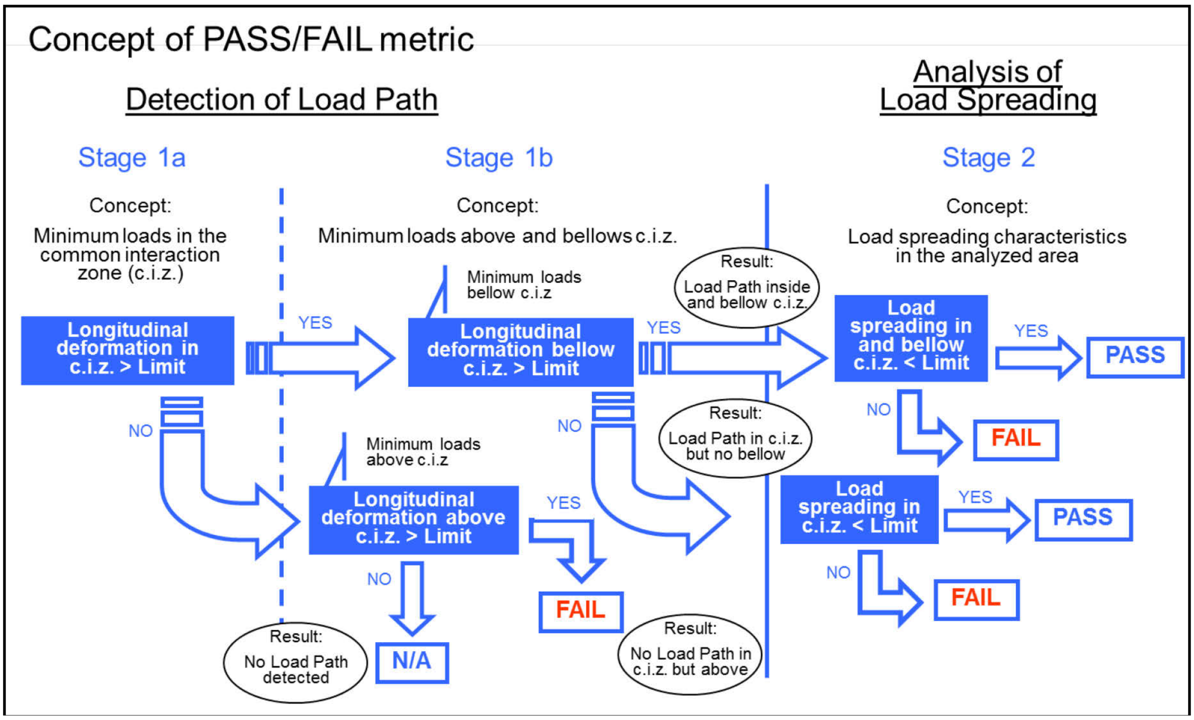


Figure 3.14: Proposal for metric.

Figure 3.14 shows the logics and concepts that are addressed by the proposed metric, the metric is believed to analyse, in a first stage, the presence of a load path and, in a second stage, the characteristics of that load path in terms of spreading the load through the barrier.

Scoring concepts like capping criteria were also investigated in the metric in order to address some relevant issues detected in compatibility. Exceeding a capping limit could indicate an unacceptable high risk of a specific issue in compatibility (i.e. over/under-ride) which will result as fail.

3.4.3 Load Path Detection (Longitudinal Deformation)

The aim of the criteria is to identify front-end structures, which are able to deform the barrier in a significant manner. The load path will be evaluated by the barrier deformation. The 3D measurements of the barrier will allow the identification of the vehicle load paths.

The load path detection will be assessed by the Longitudinal Deformation of the barrier. The Longitudinal deformation *(d)* criterion has been developed using statistics characteristics of the deformation at a defined zone, taking coefficients of the barrier longitudinal deformations.

The parameter and limits can also be used to limit the front-end stiffness controlling the maximum deformation of the barrier. Figure 3.15 shows an example of limits for detecting load paths. In this proposal also the stiffness of the vehicle will be evaluated, limiting the maximal longitudinal deformation.

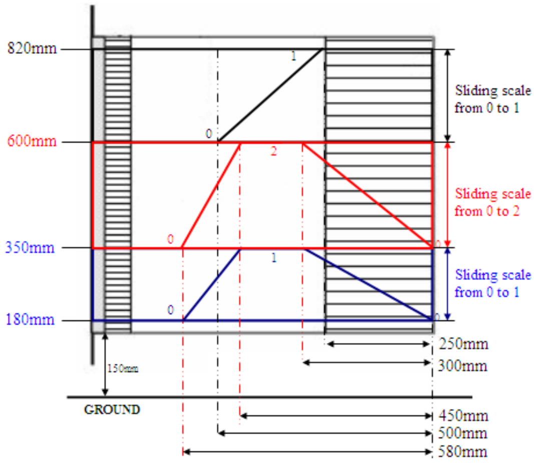


Figure 3.15: Load path detection, longitudinal deformation.

Different criteria for assessing the load path detection have been investigated.

3.4.3.1 Quantiles of Barrier Longitudinal Deformation

The **Quantiles** are points taken at regular intervals from the cumulative distribution function (CDF) of a random variable. Dividing ordered data into q equal-sized data subsets (e.g. q equal to 100 quantiles). The q numbers are the data values marking the boundaries between consecutive subsets. The presence of a load path in the defined area is assessed using q-th's% of deformation.

A minimum value for different q-th's% of longitudinal barrier deformation will be required for identifying a load path, in other words, a load path will be detected if certain q-th's% values are above certain limits.

The limits for this parameter will be established taken the PDB 60 km/h tests database as reference. Figure 3.16 shows some examples of vehicles with (red traces) and without (blue traces) SEAS able to deform the lower area of the barrier.

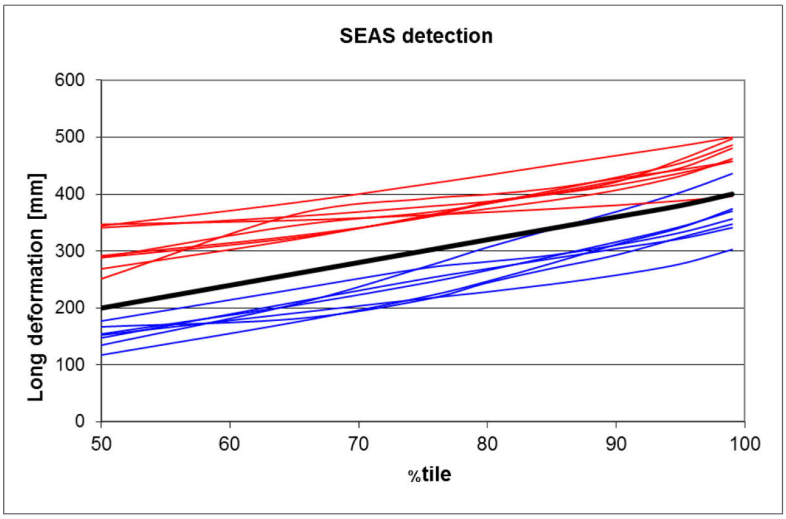


Figure 3.16: q-th% for assessing SEAS.

3.4.3.2 Mean of Longitudinal Deformation

The **Mean** is the sum of the values of a data set divided by the number of values. A minimum mean value of longitudinal deformation of the barrier will be required for identifying a load path, in other words, a load path will be detected if the mean values will be above certain limit.

The presence of a load path in the defined area is assessed using the mean of deformation of the analysed area.

The limits for this parameter will be established taken the PDB 60 km/h tests database as reference.

3.4.4 Load Spreading

The aim of this criterion is to assess the load spreading characteristics of a specific load path. This criterion is identified as a key issue for FIMCAR consortium. Therefore, its development is particularly important for the project. Several ideas have been developed for this criterion, following the more relevant ones are summarised.

The limits for these parameters will be established taken the PDB 60 km/h tests database as reference.

3.4.4.1 Total Variation (TV)

A possible criterion for assessing the load spreading is the image Total Variation. The Total Variation *(TV)* is defined as an estimation of the total amount of variation of an image, mathematically defined as the average length of contour lines (isolines) of the image. In a first stage the map (image) is filtered by an additional low-pass filter. Then, the map is normalised, so all images have the same dimension, in other words only vertical and horizontal deformations are taken into account. The gradient of the length is given the magnitude of change of slope. *TV* is proportional to the sum of lengths of the gradient of the map at all points.TV provides an estimation of the overall homogeneity of the barrier print at the investigated area. Equation 3.2 summarises the formulas used to evaluate the TV criteria.

$$\boxed{(y,z) \rightarrow x = l(y,z)} \qquad \boxed{\sum_{x,y} l(y,z)^2 = 1} \qquad \boxed{H = \int \left|\nabla l(y,z)\right| dydz}$$

Equation 3.2: Mathematical formulas for TV.

The aim of the TV criterion is to assess horizontal and vertical load spreading.

As already described in Paragraph 3.4.1 the TV value is very sensitive to sharp edges especially at boundaries of assessment zones.

3.4.4.2 Smooth Deformation Index (SDI)

In a similar way as the TV, the SDI is an estimation of homogeneity for a pre-defined assessment area. The criterion also uses the concept of calculating the sum of isolines, but not for the complete area of the barrier. The analysis is concentrated in an area with more than x percent of maximum deformation ($A_{deformed}$).

The process of calculating the criterion is summarised in Figure 3.17.

Step 1:

- Calculate size of deformed area with more than x percent (e.g. 20% ... 50%) of maximum deformation → $A_{deformed}$ (x%)

Step 2:

- Calculate sum of length of equidistant isolines (e.g. 10 mm) within $A_{deformed}$ → iso_{sumL}

Step 3:

- Calculate x percentile (e.g. 99%tile) of deformation → $def_{x\%tile}$

Step 4:

- Calculate "normalised" sum of length of equidistant isolines: $norm\_iso_{sumL} = iso_{sumL}/def_{x\%tile}$ to compensate for the vehicle weight

Step 5:

- **Calculate smooth deformation index:**
  $SDI = A_{deformed}$ (x%) / $norm\_iso_{sumL}$

Figure 3.17: Smooth deformation index (SDI) in 5 steps.

Large deformed areas and/or short length of isolines contribute to provide a high value for this criterion, which is an indicator of good level of load spreading. Complex calculation of isolines is conducted with MATLAB scripts.

As in case of TV, the SDI assesses horizontal and vertical load spreading simultaneously which can be either an advantage or a disadvantage. For the smooth deformation index analysis the assessment areas of Figure 3.6 are combined in order to reduce boundary effects.

The smooth deformation index is analysed

- for different percentages of maximum deformation (20% ... 90%, in 10% increments),
- for different percentiles of deformation (50% and 99%) and
- for different areas of investigations
  - lower and middle area combined:

    y_{min}=150 mm, y_{max}=vehicle width/2 - 100 mm; z_{min}=180 mm, z_{max}=600 mm above ground
  - lower, middle and upper area combined:

    y_{min}=150 mm, y_{max}=vehicle width/2 - 100 mm; z_{min}=180 mm, z_{max}=820 mm above ground

Since both percentiles of deformation (50% and 99%) shown mass dependent results and quite bad correlation with subjective ranking further analyses are conducted with an updated formula.

- without x percentile of deformation (step 3 and 4 of Figure 3.17 were deleted) and
- with more weight on the deformed area ($A_{deformed}$ squared).

In this approach small stiff structures are penalised by a small deformed area. Heavy vehicles having more and longer isolines can naturally compensate with a larger deformed area (e.g. with an additional load path).

Although the updated SDI shows promising results further research is needed and following open issues need to be addressed:

The sum of length of isolines is very sensitive (in accordance to the TV value) if sharp edges are located close to the boundaries of the assessment zone. This boundary issue might be solved by an assessment zone that depends on vehicle height (e.g. from 180 mm to bonnet leading edge).

In order to reduce over- /underride risk an additional requirement for the upper area might be needed to limit the deformation in the upper area.

The key advantage of SDI is that there is an indirect detection of load paths included in the formula via $A_{deformed}$ and that no stepwise approach for different assessment areas needs to be taken into account.

3.4.4.3 Area of Significant Deformations

The Area of significant deformations criterion is defined as the ratio between a measured area of deformation, A_{def}, and an ideal area of deformation, A_{ideal}, (A_{def}/A_{ideal}).

A_{def} is the area where the deformation is above a certain q% (e.g. 40%), as shown in Figure 3.18. The ideal area, A_{ideal}, is a demarcated area of deformation that takes into account the width of the vehicle (Y limits). For the vertical limits (Z limits) of A_{ideal} some investigations have been done, taking these three options of limits:

- Middle area of PDB: (400 to 600mm from ground)
- LCW Rows 3 and 4: (330 to 580mm from ground)
- Common interaction zone as defined in Part 581: (406 to 508mm from ground)

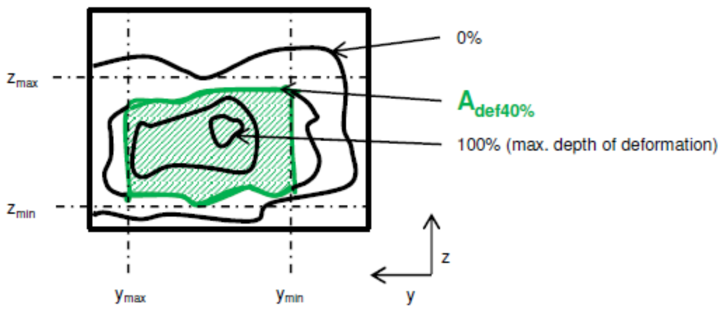


Figure 3.18: Estimation of Adef.

Values of A_{def}/A_{ideal} close to 1 will indicate a good behaviour in terms of load spreading. In case of non-homogeneous result the criteria will be close to 0.

This criterion is taking into account vertical and horizontal load spreading.

3.4.4.4 Horizontal Load Spreading

In that case the criterion is focused in horizontal load spreading. The area of investigation is divided horizontally in a total of **N** equal sub-zones. The vertical limits of overall area will be fixed (e.g. 330 to 580 mm from ground). The horizontal limits and in consequence the final size of the sub-zones will differ in function of the width of the vehicle.

Dividing the area of analysis in sub-zones allows investigating the horizontal load spreading over the total area of investigation. The further analysis of the sub-zones will be done in terms of differences of longitudinal deformations and relative distance between them.

Different parameters can be calculated from these **N** sub-zones.

- D is the average of longitudinal deformation of the complete area

- $D_{i\ (i=1\ to\ N)}$ is the average of longitudinal deformation for the i sub-zone
- $q\%_{i\ (i=1\ to\ N)}$ is the q% of longitudinal deformation for the i sub-zone

Several criteria were developed and investigated using the above mentioned parameters, some examples are:

- D/D_i gives an estimation of the horizontal variation of the i sub-zone compare to the total average
- $e_i=D-D_i$ is the deviation of a sub-zone from the overall average of deformation
- $ddy_i=q\%_i$ / $Q\%_i$ is defined as the derivation of small q% divided by larger Q%

Combining these criteria will provide an estimation of the horizontal load spreading. Figure 3.19 shows an example for this kind of analysis, for N=6. In this example some deviation for the outer part of barrier can be observed, e_1=195. Apart of that issue, the PEAS show a quite constant loading to the barrier, only D_2 is slightly above the average of area deformation.

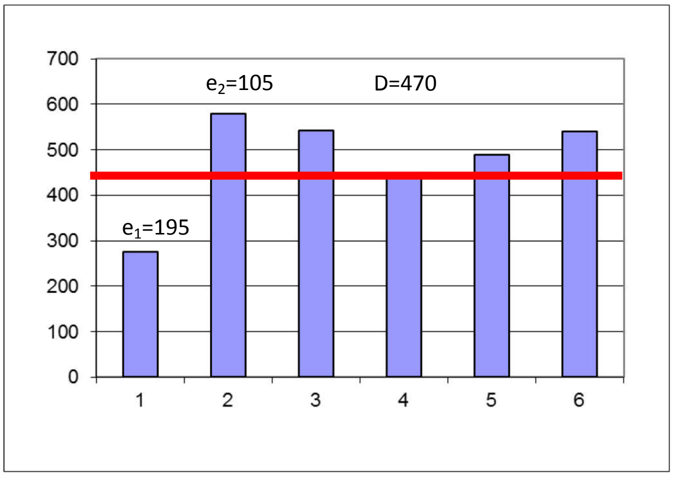


Figure 3.19: Load Spreading analysis, Di vs i.

3.5 Investigate Robustness of the Assessment Criteria and Potential for Misuse in Vehicle Design

An important requirement for the implementation of a new test procedure is the robustness of the developed metric and assessment criteria.

Corresponding investigations need to be done for the robustness of the different assessment criteria (e.g. barrier deformation, dummy injury values) via simulations and full vehicle tests.

Since the assessment criteria are mainly based on barrier deformations a key enabler for a robust assessment is the digitised deformation plot. Therefore the input for the assessment criteria has to be independent of the measurement method and the laboratory. Barrier faces will be measured by different laboratories in Task 2.2 to confirm repeatability and reproducibility of deformation plots.

Furthermore the robustness of the test procedure also depends on other test parameters (e.g. test speed, overlap, etc.). Test parameters within the specification of the test protocol must not have a significant influence on the assessment criteria. On the other hand, vehicle design parameters that have an impact on compatibility (e.g. different stiffness of crossbeam and subframe, etc.) shall have a significant influence on the assessment criteria.

In order to identify these vehicle design parameters and to determine the maximum allowed scatter for test parameters a simulation-based sensitivity analysis will be conducted using the “Parametric Car Models (PCM)” which were developed by TUB and presented in Section IV. The simulation matrix is described in more detail in section 4.1.1. Worst case scenarios of these simulations can be used to identify potential for misuse in vehicle design (e.g. strong subframe in conjunction with weak crossbeam, strong PEAS positioned in the upper area).

Additional simulations with “Generic Car Models (GCM)” which were developed by CRF and presented in Section IV were also conducted. Further details and results can be found in Chapter 4.1.2.

Overall repeatability and reproducibility of the PDB test procedure will be finally confirmed by full vehicle tests in Task 2.2.

MATLAB scripts to calculate the PDB criteria and investigate the robustness of the assessment criteria were developed in WP2. They were also used to double-check the results of the PDB crash analysis software [FIMCAR 2013].

3.6 Conclusions

Combining the load path detection and analysing the load spreading characteristics of the detected load path seems to be most adequate method to assess partner-protection issues using the off-set test procedure. The 3D measurements of the PDB will support this methodology.

The fundamentals of the assessment method using the PDB 60 km/h off-set test were defined. Different criteria and metrics were investigated for assessing compatibility issues.

The TV and TV upgrade criteria, in combination with the longitudinal deformation criterion, have shown a good correlation with a subjective assessment. However, the complexity of the TV methodologies and some issues like the important punishment that are caused by sharp edges of barrier deformation makes the TV criteria a non-suitable methodology to be further proposed.

Another promising criterion for assessing the load spreading, the area of significant deformations, was also analysed. However, the criterion was also discarded due to the bad correlation showed with the subjective classification.

For its simplicity and some promising correlation results, the horizontal load spreading seems the best option for evaluating the load spreading of a detected PEAS and SEAS. However, it was not possible to deliver a robust compatibility metrics for the PDB in time to be considered within the FIMCAR project. Nevertheless the FIMCAR consortium agreed to further develop the load spreading criteria based on the concepts of the horizontal load spreading criteria.

The final assessment methodology will be defined following the priorities that will be identified in FIMCAR, the basics have been established as shown in Equation 3.2. The PDB metrics including limits needs to be further developed and validated using the upcoming tests that will be performed in FIMCAR project.

During the testing and simulation activities of the project, the test severity has been also investigated. The conclusions in regards to this issue can be found in Section 4.1.1 of this report.

4 TESTING AND ANALYSIS OF TEST PROCEDURE

4.1 Simulations Performed for the Criteria Development

As already described in section 3.5 simulations were requested

- To investigate the robustness of the metric and assessment criteria and
- To identify potential for misuse in vehicle design.

WP5 performed some simulations with “Generic Car Models” (GCM) developed by CRF and conducted a sensitivity analysis with “Parametric Car Models” (PCM) developed by TUB that are included in this report.

More details regarding vehicle models and modelling techniques can be obtained in Section IV.

4.1.1 Simulations with Generic Car Models (GCM)

GCM models with and without sub-frame load path were used to simulate PDB tests at 60 km/h and with 50% offset according to PDB test protocol [ECE 2007].

- GCM1_A: Supermini without sub-frame load path
- GCM1_B: Supermini with sub-frame load path
- GCM2_A: Small Family Car with sub-frame load path
- GCM2_B: Small Family Car without sub-frame load path
- GCM3_A: Large/Executive Car with sub-frame load path

Figure 4.1 shows the GCM1A and GCM1B barrier deformation results. For the simulation runs with GCM an internal CRF PDB model was used.

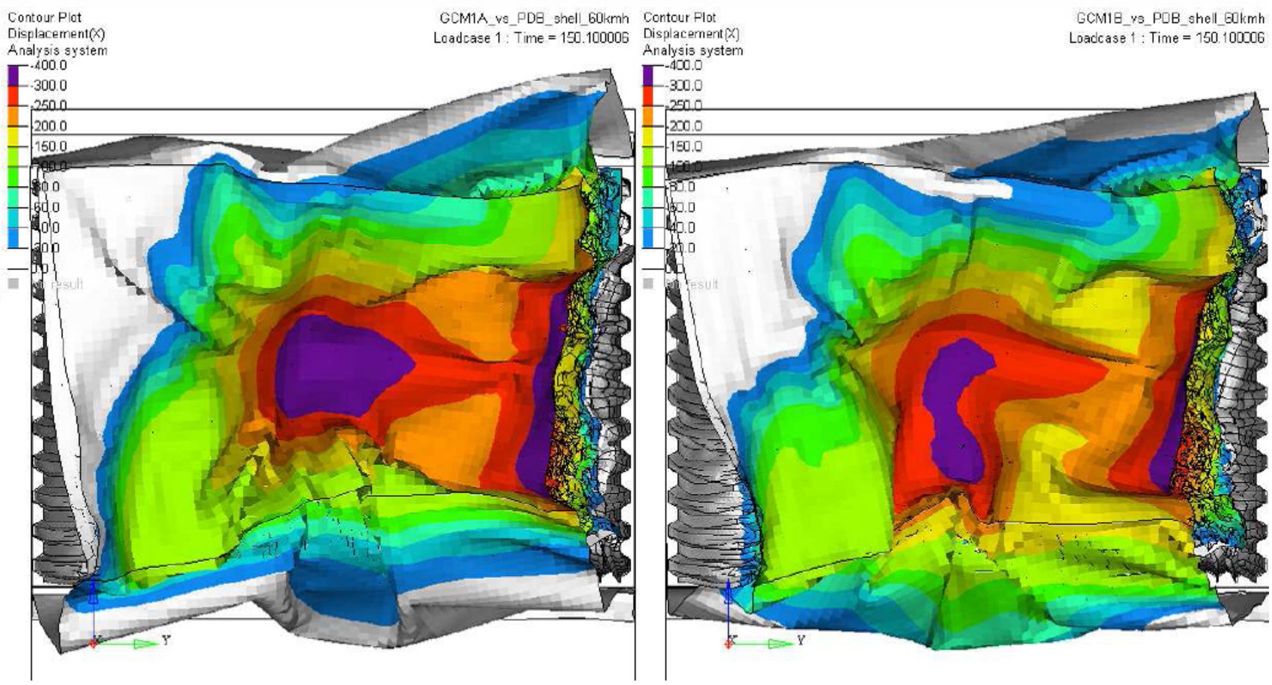


Figure 4.1: GCM1A and GCM1B barrier deformation.

As shown in Figure 4.1, the subframe of GCM1B deforms more the barrier at the lower area than GCM1A that does not have a subframe. This is numerically reflected by the lower longitudinal deformation for GCM1A (243 mm) compared to GCM1B (310 mm).

Table 1 shows the summary results that were analysed with BDA soft (v12.2010) [FIMCAR 2013], in the summary results, the longitudinal deformation is represented by the 99% of deformation and the load spreading (H) by TV criterion.

Table 1: GCM – PDB results.

Model	Simulation results			Results from BDA software [FIMCAR 2013]				
	Barrier Energy [kJ]	EES [km/h]	Force [kN]	Barrier Volume [l]	U Area 99% long. def. [mm]	M Area 99%long. def. [mm]	L Area 99%long. def. [mm]	M Area TV [-]
GCM1_A	62.9	42	343	135	281	346	243	1656
GCM1_B	63.6	42	357	133	236	314	310	1732
GCM2_A	82.3	40	391	166	664	365	336	1202
GCM2_B	82.4	41	381	152	595	359	309	1430
GCM3_A	129.1	36	444	249	717	507	444	1546

The numerical simulation work is a good methodology to assess the PDB test severity. In this kind of study, the PDB deformation can be analysed using the numerical methodology, which reduces the number of errors always existing in the actual testing.

As reported from the PDB test database, the test severity for the PDB has been identified as an issue in WP2. The GCM analysis supported this investigation. The variety of vehicles represented by these models in terms of vehicle sizes and front-end structures gave the possibility to conduct an analysis focused on the test severity for this family of vehicles.

The models were tested following the PDB 60 km/h and the ODB 56 km/h (test reference) configurations. Vehicles from different sizes and front-end structures were simulated in equal test conditions. Output parameters like maximal intrusions, EES and accelerations can be used to estimate the test severity for the different models.

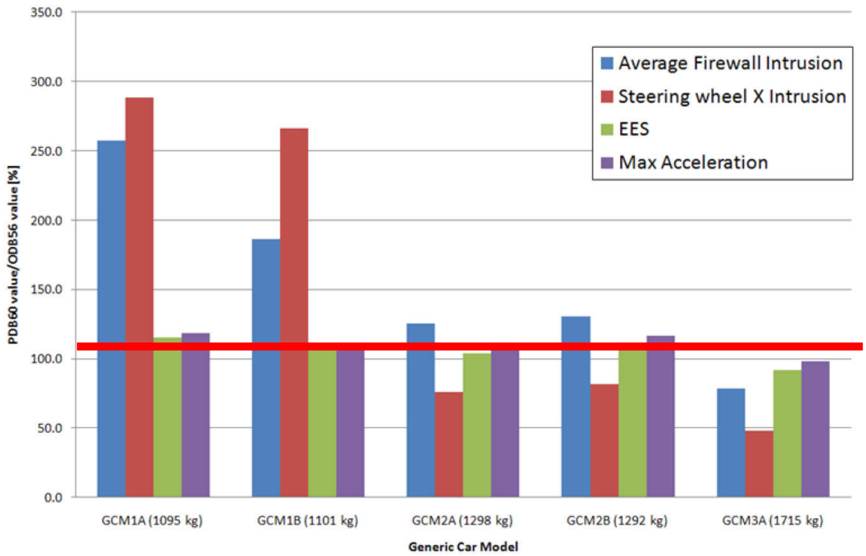


Figure 4.2: GCM – ODB vs. PDB results.

Figure 4.2 shows the test severity results for the 5 GCM vehicles comparing PDB60 against ODB56. The intrusion results were obtained from the maximal dynamic value. These values are considered to be slightly higher than the static ones, typically reported in physical testing.

The EES and the Max Acceleration seem to be the more appropriate criteria to assess the level of test severity. As it can be shown in Table 1, for the super-minis and small family cars the test severity is supposed to be higher for the PDB60. The opposite is observed in the case of the GCM3A (large executive vehicle), the EES in the PDB60 is about 10% below the ODB56.

This result is confirming the estimations from the PDB60 database, Figure 3.3, where for certain kind of vehicles the PDB represents a slightly more severe test that the ODB56 while in some large and stiff vehicle the opposite is observed.

4.1.2 Simulations with Parametric Car Models (PCM)

The requested simulations with PCM will be also conducted according to the test-setup of PDB test protocol [ECE 2007] with a PDB barrier offset of 50% and a vehicle velocity of 60 km/h.

In total 3 different types of cars (executive car, large family car and supermini) were modelled as PCMs. Based on the parametric design of the basis model the 3 models were generated with typical structural concepts. Therefore, the supermini model was designed without a sub-frame. Due to the fact that the engine of the large family car is very close to the cross-beam it was decided to use the executive car for the sensitivity analysis.

Figure 4.3 shows the PCM - Executive car FE-model, for the simulation runs the FIMCAR PDB model developed by GME was used:

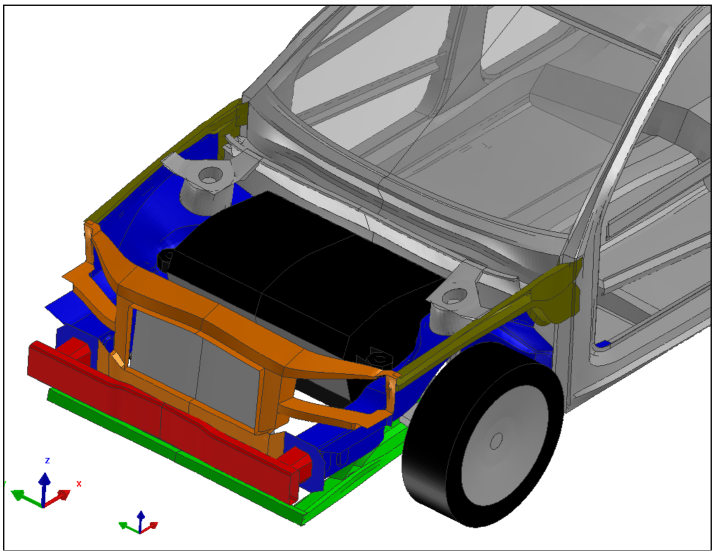


Figure 4.3: PCM – Executive car.

The requested sensitivity analysis will investigate the influence of different parameters on the PDB assessment criteria and developed metrics. These parameters are geometric parameters, describing the position and the stiffness of several structures, and crash severity parameters like vehicle mass and closing speed.

Table 2 shows a summary of the number of simulation to run.

Table 2: Simulation matrix for PCM.

Parameter of study	Number of runs	Priority
Vehicle mass	5	3
Test speed	5	3
Cross-beam stiffness	5	1
Cross-beam height	5	2
Cross-beam length (Y-direction)	5	2
Sub-frame length (X-direction)	5	2
Sub-frame stiffness	5	1
Sub-frame height	5	2
Sub-frame length (Y-direction)	5	2

In addition some worst case runs without crossbeam resp. collapsed crossbeam in order to produce holes in the barrier are planned.

Due to budget limitation simulation runs were prioritised as follows:

- 1st priority: stiffness of cross beam and sub frame
- 2nd priority: geometrical variations (width and position of structures)
- 3rd priority: vehicle mass and initial velocity

First simulation results indicated PDB barrier model (Version 1.0) quality issues that had to be further investigated to improve the validation of the barrier model. It will be validated against the barrier certification tests (trolley tests with rigid impactors) comparing force-displacement curves and scanned barrier deformations. Furthermore especially rupture of the cladding plate will be taken into account.

For this reason no conclusions regarding the sensitivity analysis can be drawn in this report.

4.2 Tests Performed for the Criteria Development

At the date of December 2011, a total of 3 tests were performed in WP2. Table 3 shows the up-to-date test matrix and the main objective of each test. WP2 plans to continue with the testing phase until the end of the project. The main objective of the coming tests will be the final development of the assessment procedure and prove the repeatability and reproducibility of the assessment.

Table 3: Test matrix.

Vehicle to test	Laboratory	Test Date	Test configuration	Objective	Partner-protection
Supermini 2	FIAT	Jun 2011	PDB60 [3]	Test severity validation (self-protection) and comparison with other test modes (FWRB and MPDB)	Good performance expected
City Car 1	UTAC	Sep 2011	PDB60 [3]	Comparison with FIAT 500 in terms of the vehicle performance	Good performance expected
Supermini 1	PSA	Nov 2011	PDB60 [3]	Test severity validation (self-protection) and validation of the compatibility assessment	Marginal performance expected
Supermini 2	BASt	Jan 2012	PDB60 [3]	Repeatability issues	Good performance expected

The tests performed relate to Task 2.2. Table above shows a total of 4 tests performed within WP2 following the PDB60 test procedure as defined in the EEVC proposal for amendment, details can be found at [ECE 2007]. The test consists on a 50% off-set against a Progressive Deformable Barrier (PDB) at a target speed of 60 km/h. In the test, 2 ATD HIII 50%ile Males were seated at the driver and front passenger positions, the dummies are used to estimate the level of injuries caused by the crash test.

4.2.1 Supermini 2 Test

Supermini 2 was selected with the objective of evaluate the PDB60 test severity and confirm the good performance of the vehicle in terms of partner-protection.

In order to evaluate the test severity different test pulses for Supermini 2 were compared (all tests from FIMCAR database). Figure 4.4 gives an estimate test severity level normalised to the USNCAP maximal acceleration peak.

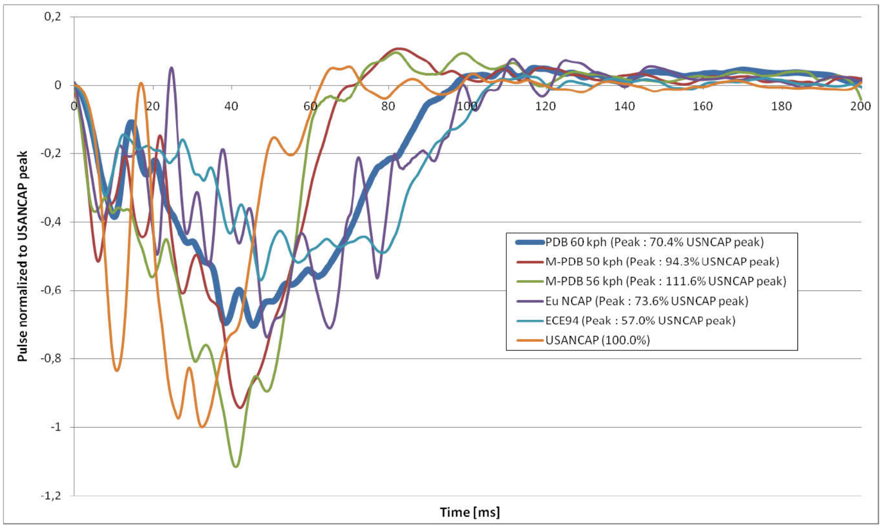


Figure 4.4: Supermini 2 B-pillar pulses.

Figure 4.4 shows Supermini 2 pulse at the driver's side for different kind of tests. As shown in the graph the PDB60 curve, dark-blue, is very close to the Euro NCAP one.

It is well known that the Euro NCAP (ODB64) test is more severe than the UNECE R94 test (ODB56). Then, for this particular case and taking the acceleration response as reference, we can conclude that the PDB60 represents a more severe test than the ODB56, light-blue trace in the graph. In terms of vehicle intrusions Supermini 2 achieved a very low A-pillar displacement, 1 mm for both cases, PDB60 and ODB56.

Regarding partner-protection issues, Supermini 2 loaded the middle and lower area of the barrier as shown in Figure 4.5. The load spreading for the middle area was particularly good.

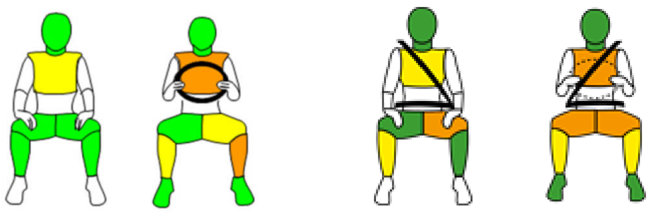
PDB60 MPDB50

Figure 4.5: PDB deformation Supermini 2.

Barrier deformation for the PDB60 and the MPDB50 test show similar pattern. This shows the general repeatability and robustness of the barrier deformation even under completely different crash conditions. However, there is a rupture in the front plate of the PDB60 test while it could not be observed in the MPDB test.

4.2.2 City Car 1 Test

In this case the test severity between PDB60 and ODB64 was also comparable, dummy readings have been compared, Figure 4.6.



PDB60 Euro NCAP [Euro NCAP 2013]

Figure 4.6: City car 1 dummy results.

In both test configurations driver and passenger dummy were loaded in a similar manner. Head injuries were below the Euro NCAP higher performance [Euro NCAP 2013], 5% risk of injury ≥AIS3. Driver and passenger's chest were loaded likewise in both tests. The driver's chest had a higher injury risk compare to the passenger. The injuries at the lower extremities were also comparable, driver legs recording higher values than passenger for both test configurations.

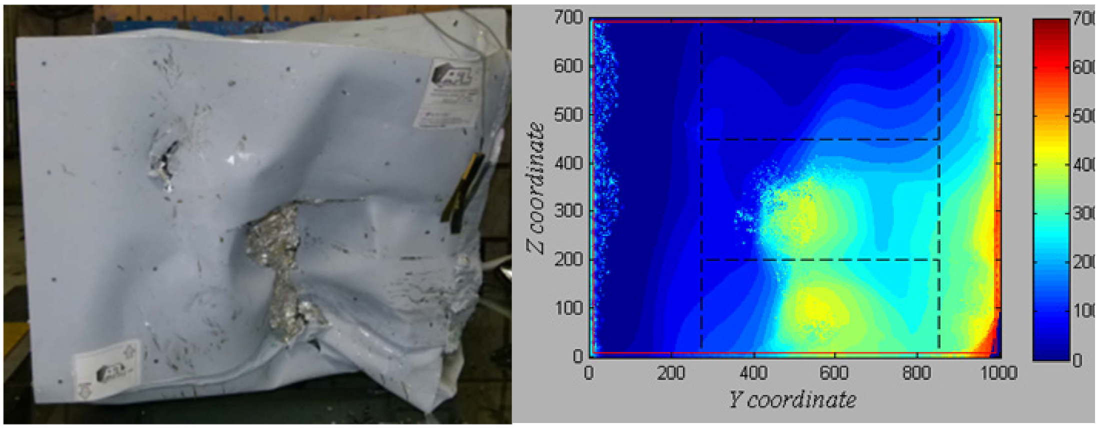


Figure 4.7: PDB barrier deformation of City car 1.

The PEAS and SEAS of City car 1 loaded the middle and lower area of the barrier respectively, Figure 4.7. The load spreading for the middle area was marginal.

4.2.3 Supermini 1 Test

The Supermini 1 crash pulse achieved a maximum peak of about 40 g. Figure 4.8 shows the B-pillar acceleration against vehicle displacement.

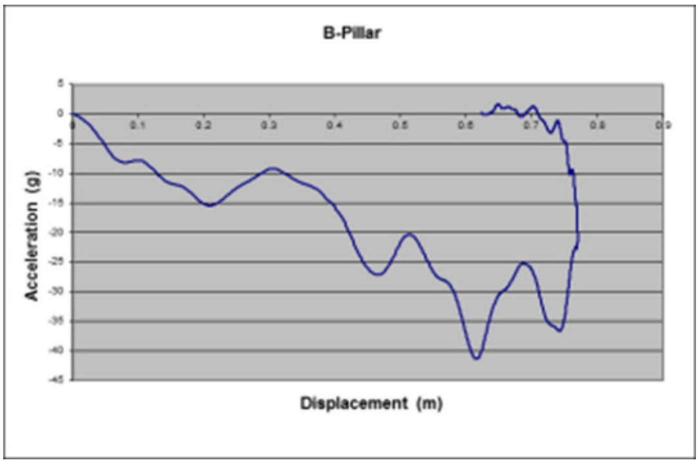
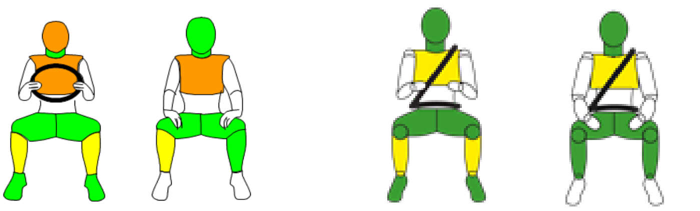


Figure 4.8: Supermini 1 PDB60 crash pulse.

Figure 4.9 shows the dummy results for PDB60 and Euro NCAP tests. The overall results in both tests are equivalent. It is remarkable that there are higher chest injury risks for both occupants in the PDB test compared to the Euro NCAP.



PDB60 Euro NCAP [Euro NCAP 2013]

Figure 4.9: Supermini 1 dummy results.

In terms of vehicle intrusions Supermini 1 achieved a low A-pillar displacement, 23 mm in the Euro NCAP test and 17 mm in the PDB60.

The PEAS of Supermini 1 loaded the middle and lower area of the barrier respectively, the load spreading for the middle area was marginal, Figure 4.10. The lower part of the barrier was not deformed. Therefore no SEAS have to be detected for this car.

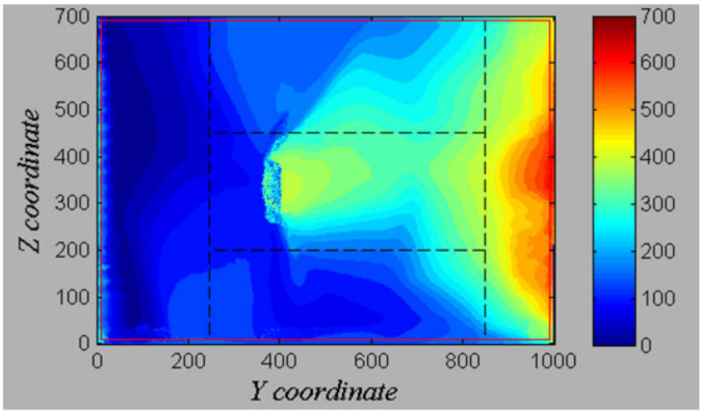


Figure 4.10: Supermini 1 PDB barrier deformation.

4.3 Conclusions

Simulation and testing work conducted in WP2 show that PDB test severity is comparable with the severity for the ODB test procedures (R94 / Euro NCAP). In particular, the PDB seems to be a slightly more severe test procedure for most of the small and light vehicles, while for some large car the severity is slightly below the current ODB56 approach. For example, the three vehicles tested in WP2 following the PDB tests seems to be at the similar level of ODB64 and therefore above the ODB56. But as simulation results show for the GCM3 model (large executive car), the PDB test appear to be less severe than the ODB56. This result correlates with the trend for PDB database.

WP2 plans to conduct more testing activities with large vehicles in order to try to validate the result obtained by simulation work and the database.

The PDB results obtained in this testing series will be further used for developing the partner-protection criteria proposed in WP2.

5 DISCUSSION AND CONCLUSIONS

The current ODB procedures assess the self-protection of the tested vehicle. There are no methodologies investigating the partner-protection (e.g. structural interaction or frontal force levels).

According to the accident analysis performed in FIMCAR, reported in Deliverable D1.1 and Section II, self-protection topics like passenger compartment intrusions and high acceleration are still an issue on the road. The present ODB test procedure addresses these self-protection issues and therefore the procedure is still valid to maintain today's self-protection level.

The test results obtained in the project with the PDB highlighted that the severity of this test procedure was comparable to the current ODB tests for most of the analysed cars. Therefore, the PDB test seems to be an acceptable method to evaluate self-protection issues except for very heavy vehicles.

Self-protection issues could be also assessed by PDB test procedure, the tools and methodology to assess self-protection can be adopted from the current ECE R94 test.

In order to address some partner-protection issues, also reported in FIMCAR's accident analysis, WP2 has identified the PDB test procedure as the most promising methodology. The fundamentals for assessing partner-protection issues with the PDB approach have been defined.

The PDB methodology consists of assessing the barrier deformation. The PDB will be vertically divided in zones as shown in Figure 5.1. The 350 to 580 mm from ground area is harmonised with the FW methodology, this area includes the CIZ.

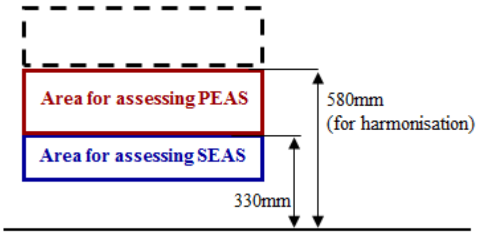


Figure 5.1: PDB areas of assessment.

The structural interaction was defined as the main issue for improving the partner-protection of a vehicle. The vertical location of the load paths, assessed by the barrier deformation caused by the longitudinal, provides an estimation how the tested vehicle will interact with an opponent car.

First priority was established on detecting the vehicles load paths in the CIZ and below that zone.

The contribution of the SEAS was defined as an added value to contribute in partner-protection issues. 50 to 65% of longitudinal deformation, or mean deformation, were identified as the most promising parameters to detect the load paths, Figure 5.2 shows the result of the PDB60 database for SEAS detection.

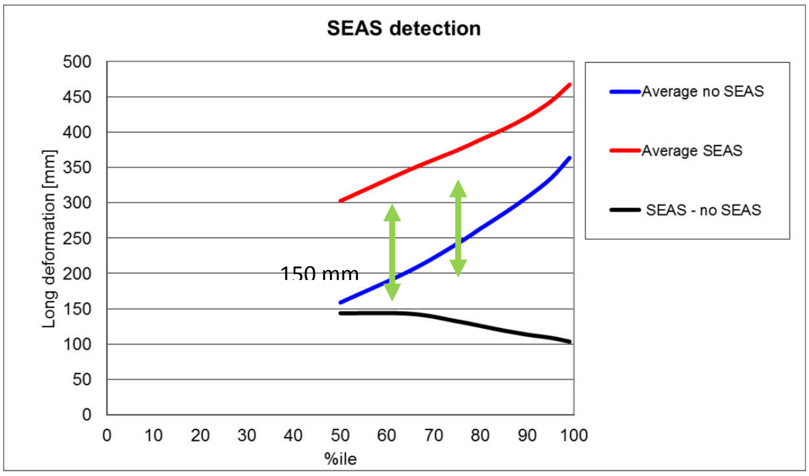


Figure 5.2: Load path detection.

The load spreading in the CIZ was also identified as a main issue to be addressed by the PDB procedure. Several proposals for assessing the characteristics of the load spreading were investigated in WP2. The load spreading criterion will focus on assessing the horizontal load distributions in the area where the CIZ is located. This criterion will be addressing compatibility issues like the small overlap and the fork effect.

Although the subjective assessment of PDB barrier scans is promising to rate the load spreading it was not possible to develop a PDB metrics that is robust enough to propose the PDB as part of the FIMCAR frontal impact assessment approach. The ODB56 will be kept in order to maintain current self-protection requirements. However, PDB might still be an option for the future when a validated compatibility metrics can be proposed.

It should be noted that work to develop compatibility metrics for the PDB test will continue within the project because the FIMCAR members believe that the PDB test has potential for compatibility assessment in the longer term.

6 REFERENCES

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7 GLOSSARY

ATD:	Anthropomorphic Test Device
BDA:	Barrier Deformation Analyser
CIZ:	Common interaction zone (as described in Part581 zone)
EES:	Energy Equivalent Speed
EEVC:	European Enhanced Vehicle Safety Committee
Euro NCAP:	European New Car Assessment Programme
FW:	Full Width Frontal Impact
GCM:	Generic Car Models
HIII:	Hybrid III test dummy
IIHS:	US Insurance Institute
LCW:	Load Cell Wall
NHTSA:	US National Highway Traffic Safety Administration
ODB:	Off-set Deformable Barrier Test (current ECE R94/Euro NCAP)
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PCM:	Parametric car models
PDB:	Progressive Deformable Barrier
PEAS:	Primary Energy Absorbing Structures
SEAS:	Secondary Energy Absorbing Structures
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility

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FIMCAR
VI – Off-Set Test Procedure: Updated Protocol

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The off-set assessment procedure potentially contributes to the FIMCAR objectives to maintain the compartment strength and to assess load spreading in frontal collisions. Furthermore it provides the opportunity to assess the restraint system performance with different pulses if combined with a full-width assessment procedure in the frontal assessment approach. Originally it was expected that the PDB assessment procedure would be selected for the FIMCAR assessment approach. However, it was not possible to deliver a compatibility metric in time so that the current off-set procedure (ODB as used in UNECE R94) with some minor modifications was proposed for the FIMCAR Assessment Approach. Nevertheless the potential to assess load spreading, which appears not to be possible with any other assessed frontal impact assessment procedure was considered to be still high. Therefore the development work for the PDB assessment procedure did not stop with the decision not to select the PDB procedure.

As a result of the decisions to use the current ODB and to further develop the PDB procedure, both are covered within this deliverable. The deliverable describes the off-set test procedure that will be recommended by FIMCAR consortium, this corresponds to the ODB test as it is specified in UN-ECE Regulation 94 (R94), i.e. EEVC deformable element with 40% overlap at a test speed of 56 km/h. In addition to the current R94 requirements, FIMCAR will recommend to introduce some structural requirements which will guarantee sufficiently strong occupant compartments by enforcing the stability of the forward occupant cell.

With respect to the PDB assessment procedure a new metric, Digital Derivative in Y direction - DDY, was developed, described, analysed, and compared with other metrics. The DDY metric analyses the deformation gradients laterally across the PDB face. The more even the deformation, the lower the DDY values and the better the metric’s result.

In order analyse the different metrics, analysis of the existing PDB test results and the results of the performed simulation studies was performed. In addition, an assessment of artificial deformation profiles with the metrics took place. This analysis shows that there are still issues with the DDY metric but it appears that it is possible to solve them with future optimisations. For example the current metric assesses only the area within 60% of the half vehicle width. For vehicles that have the longitudinals further outboard, the metric is not effective.

In addition to the metric development, practical issues of the PDB tests such as the definition of a scan procedure for the analysis of the deformation pattern including the validation of the scanning procedure by the analysis of 3 different scans at different locations of the same barrier were addressed. Furthermore the repeatability and reproducibility of the PDB was analysed. The barrier deformation readings seem to be sensitive with respect to the impact accuracy.

In total, the deliverable is meant to define the FIMCAR off-set assessment procedure and to be a starting point for further development of the PDB assessment procedure.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self and partner-protection level) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition, another procedure (tests with a moving deformable barrier) is under discussion in today's research programmes.

Within the FIMCAR project, different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to summarise the FIMCAR activities regarding the off-set assessment procedure and to present the FIMCAR final off-set assessment procedure. In detail the following items are covered:

- Final off-set test protocol
- Reporting of crash test data
- Reporting of the Repeatability and Reproducibility analysis
- Analysis of test severity
- Proposal for off-set assessment criteria and metric
- Analysis of scanning issues for the PDB

1.3 Structure of this Deliverable

The deliverable starts with the definition of the FIMCAR off-set assessment procedure and the justification for its selection. Chapter 3 summarises the FIMCAR off-set test results, followed by further developments of the PDB procedure (metric development, PDB scanning procedure, analysis of test severity).

2 PROTOCOL FOR OFF-SET TEST PROCEDURE

The FIMCAR decision of an off-set test procedure consisted of maintaining the ODB test as it is specified in UN-ECE Regulation 94 (R94), i.e. EEVC deformable element with 40% overlap at a test speed of 56 km/h with no load cell wall or barrier assessments. An additional requirement on vehicle intrusions is proposed to ensure that all vehicles have a stable occupant compartment.

The main reasons for selecting the **Offset Deformable Barrier (ODB)** for the offset test procedure are:

- ODB guarantees that current level of compartment strength will be maintained for all vehicles
- Used in legislated and consumer tests in many countries
- Provides a softer pulse compared to the full width (FW) test
- Harmonization potential
- PDB without reliable compatibility metrics was not acceptable for a majority of FIMCAR members

The addition of a requirement for A-Pillar deformations to be less than 50 mm will guarantee sufficiently strong occupant compartments by enforcing the stability of the forward occupant cell. There is no explicit requirement for compartment stability in the current R94 that ensures a minimum level for Europe. Euro NCAP tests tend to promote stronger compartment designs than R94 but this is not a mandatory test.

The ODB test, as it is specified in R94, is characterized by an overlap of 40% impacting in driver's side at a test speed of 56 km/h [EEVC 2013]. The deformable barrier used in this test was developed by the European Enhanced Vehicle Safety Committee (EEVC) in the 90's, its characteristics in terms of stiffness corresponds to a passenger car developed during this period. The details of the test and assessment protocol for the proposed Off-set test are described in the Annex A of this report.

For vehicles developed after the implementation of the R94 the barrier is bottomed out in almost every test, as consequence of the barrier bottoming out, the main impact occurs with the rigid wall, therefore, the ODB test leads to a severe loading of the structures and, in particular, to the cabin intrusions.

Hybrid III (HIII) ATD's are used to evaluate the self-protection of the vehicle which is assessed through the dummy injury values. The HIII measures the likely injuries in this type of crash. In addition to the HIII assessment, the residual rearward displacement of the A-Pillar (adjacent to the upper hinge of the front door) will be measured. The A-Pillar intrusion gives an indication of the integrity of the passenger compartment. Large displacements are usually associated with catastrophic collapse of the roof, driver's door and floorpan. A-Pillar displacements greater than 50 mm in the ODB 56 km/h test are considered as a potential control for passenger compartment integrity.

3 SUMMARY OF TESTS PERFORMED

3.1 PDB Tests

Two off-set candidates were evaluated in WP2, the ODB and PDB test procedures, as described in D2.1 [Lazaro 2013]. The PDB was identified at the start of the project as the one with more potential to evaluate the issues and priorities defined in FIMCAR, but still some open issues need be addressed, see Figure 3.1.

FIMCAR's consortium identified 8 main priorities to be addressed for frontal impact protection, see Figure 3.1. Not all these priorities are necessarily needed to be evaluated in an off-set procedure if it is combined with the full width test in a common frontal impact protection assessment. The main issues that are expected to be evaluated in an off-set procedure are the load spreading issues (Structural Interaction) and the self-protection in regards to compartment strength. In addition, the combination of a full width and off-set test provide a possibility to evaluate the restraint system for different pulses.

Figure 3.1 summarises the list of issues to be addressed by the frontal impact protection assessment test procedures. Both off-set test candidates were evaluated with respect to these priorities and the PDB was identified as the one with more potential to address the below described priorities.

	Structural Interaction		Front End Force / Deformation		Compartment Integrity		Restraint System	
	Alignment	Load Spreading	Deforma-tion force	Energy Absorption	Sufficient for self-protection	Enhanced for light vehicles	Different pulses	Restraint Capacity
Priority	**1**	**1**	**2**	**1**	**1**	**2**	**1**	**1**
Can be addressed by? (FIMCAR conclusions)								
ODB	N	N	N	-	Y	N	-	-
PDB	Y	?	Y	-	?	Y	-	-

Metric development **Test procedure characteristics**

Figure 3.1: FIMCAR priorities and off-set candidates.

Regarding the two off-set candidates, only the PDB has the potential to assist in evaluating structural alignment (load spreading). The PDB provides the final deformed shape of the barrier at the end of crash. That gives an indication about how the tested vehicle will interact with a partner vehicle in case of a car-to-car collision.

After the initial analyses performed within WP2, some of the issues in Figure 3.1 needed to be further investigated. In case of the ODB, as its potential to address the compartment integrity issue was limited, there were no additional items to be proved or reviewed. Therefore, the FIMCAR off-set test series was focused on the PDB test procedure.

Although the PDB also gives the possibility of assessing the front-end forces of the tested vehicle, which may be desirable for assessing force level matching between vehicles, the accident data in WP1 did not indicate that this issue was a high priority for current FIMCAR activities.

The main issues to be addressed in the PDB test campaign were:

- Structural Interaction (Load spreading)
- Compartment integrity (Sufficient for self-protection)

A total of 7 PDB tests were performed in WP2. Table 1 shows the complete test matrix and the main objective of each test. In addition to the above objectives, this testing program will support the final development of the assessment procedure and support the repeatability and reproducibility (R&R) evaluation of the PDB approach.

Table 1: PDB Test matrix.

Vehicle to test	Laboratory	Test Date	Test configuration	Objective	Partner-protection
Supermini 2	FIAT	Jun 2011	PDB60	Test severity validation (self-protection) and comparison with other test modes (FWRB and MPDB)	Good performance expected
City Car 1	UTAC	Sep 2011	PDB60	Comparison with Supermini 2 in terms of the vehicle performance	Good performance expected
Supermini 1	PSA	Nov 2011	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	Marginal performance expected
Supermini 2	BASt	Jan 2012	PDB60	Repeatability issues	Good performance expected
Supermini 2	BASt	Apr 2012	PDB60	Repeatability issues	Good performance expected
SUV 1	IDIADA	May 2012	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	Good performance expected
Small family Car 1 (SFC 1)	IDADA	Jun 2012	PDB60	Test severity validation (self-protection) and validation of the compatibility assessment	PASS/FAIL limit investigation

A detailed test report and analysis of these 7 tests can be found in Annex E of this deliverable. The main objective of FIMCAR's off-set testing activities was addressing the different issues pointed out by the project, as well as answering to the R&R issues of the PDB test procedure.

In order to address the compartment strength issues the following items were analysed.

3.1.1 Pulse

The vehicle test pulse for all the tests was measured at the B-pillar base. The vehicle pulse gives an estimation of the test severity in terms of deceleration. A higher deceleration will indicate a higher severity of the test. The duration of the pulse will serve as an indicator of the severity, shorter durations will suggest higher severities.

Figure 3.2 shows the vehicle pulse of all the PDB tests performed. The graph shows the tendency that the small vehicles have the highest deceleration peak (i.e. City Car 1, Supermini 1 and Supermini 2) compared to the heavy ones. In particular, a significantly lower peak was observed for the heavy vehicle (SUV 1). The mid-size car, SFC 1, is located in between both categories of vehicles.

A similar trend is observed in terms of pulse duration. Vehicles with higher deceleration peaks reached 0 m/s earlier than vehicles with lower peak. A significant difference is observed between the SUV 1 and the small vehicles, in particular Supermini 2 and City Car 1. In all cases an equivalent delta velocity (DV) is observed.

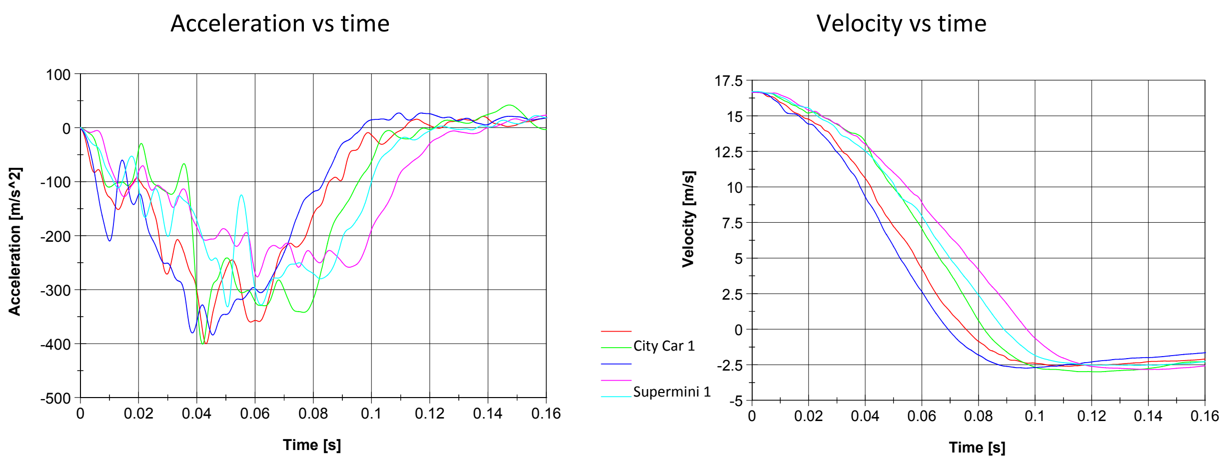


Figure 3.2: Tested vehicles pulse.

Parameters like the *max mean acceleration*, Equation 3.1, also serves to evaluate the level of severity and compare the severity of different test procedures and between vehicles.

$$max\,mean\,acc = \frac{max\,Delta\,V}{time\,to\,max\,DeltaV}$$

Equation 3.1: Max mean acc.

The max mean acceleration of the different PDB tests has been compared. The results are summarised in Figure 3.3. The Supermini 2 shows a significantly higher value compared to the others, the lowest value is the SUV 1, followed by the SFC 1. Therefore, we can confirm that the Supermini 2 test was more severe in terms of deceleration pulse compared to the others.

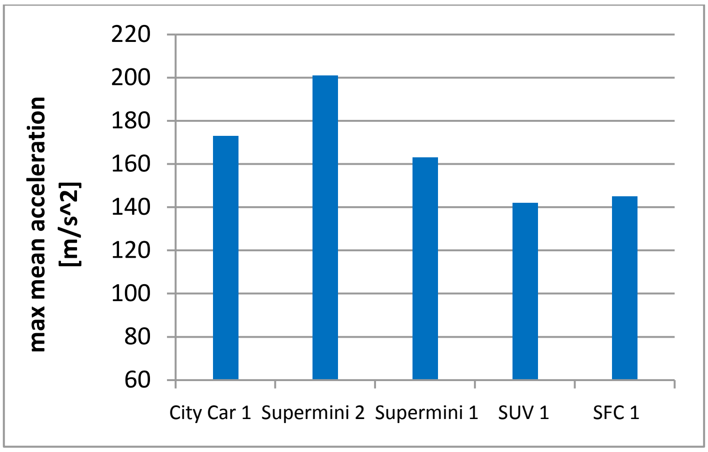


Figure 3.3 Tested vehicles max mean acceleration.

The Supermini 2 PDB test achieved even higher decelerations than the corresponding Euro NCAP [Euro NCAP 2013] test. As result, a high mean acceleration is also observed in the PDB test, 205 compared to 177m/s^2. Although no data was available, it is expected that the R94 test will record a significantly lower value than the other two tests.

The PDB pulse is generated by the deformation of both barrier and vehicle, with similar contributions from each of them. In the Euro NCAP test, the ODB barrier's contribution is significantly lower than the vehicle's. On the other hand, in the Euro NCAP test the vehicle sill is loaded while in the PDB test no deformation is observed in this area.

Euro NCAP test PDB test

Figure 3.4 Supermini 2 PDB vs. Euro NCAP

No deformation of the sill load path was observed in all PDB tests performed in WP2, independent from the type of tested vehicle. In Figure 3.4 we can appreciate the local deformation of the Euro NCAP test at the sill area. The deformation suggests a loading in the structure and, as consequence, the contribution of the load path to the deceleration pulse.

3.1.2 Intrusions

The residual displacement of structural components in the passenger compartment provides an indication of the level of self-protection offered by the tested vehicle, i.e. the A-pillar rearward displacement. The passenger compartment will be loaded during the crash and the A-pillar will be displaced rearwards. In other words, the intrusions can be interpreted as a direct indication of the response of the vehicle the passenger loading. The A-pillar intrusion, or lack of, will indicate a level of self-protection of the tested vehicle.

The European vehicles influenced by Euro NCAP (almost all vehicles today in Europe) produce a very low A-pillar rearward displacement in any off-set test (R94, Euro NCAP or PDB). This is also the case for the vehicles that were tested against the PDB in FIMCAR, in all cases below 30 mm. Figure 3.5 shows the results of the A-pillar intrusions for these vehicles.

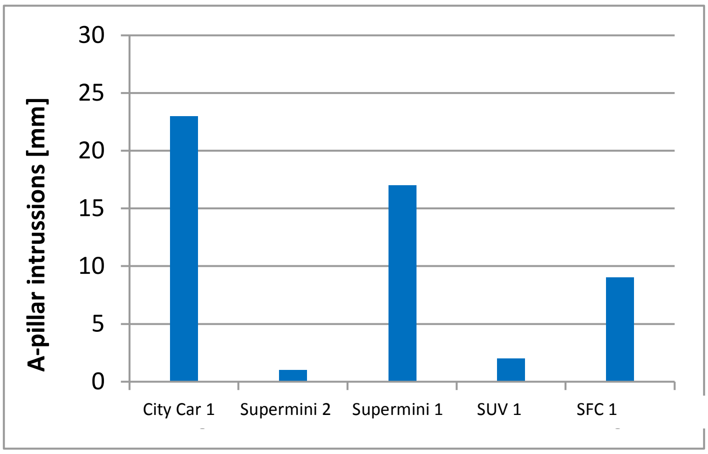


Figure 3.5: Tested vehicles A-Pillar intrusion.

3.1.3 Dummy Loadings

The dummy injuries are a direct indication of the level of self-protection provided by the tested vehicle. The protection provided by the car during the frontal impact test is measured by the ATD, HIII 50%tile male dummy, as it is specified by today's ECE R94 frontal off-set test [EEVC 2013].

In WP2 tests, the injury parameters are compared to the Euro NCAP [Euro NCAP 2013] scale in order to provide an estimation of the level of protection provided by the vehicle and compare the PDB severity to the Euro NCAP rating.

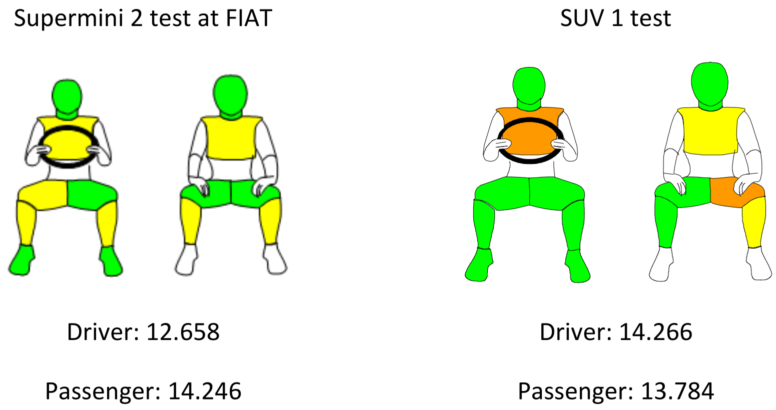


Figure 3.6 PDB tests dummy results.

The figure above shows the dummy results of two PDB tests performed by WP2, Supermini 2 and SUV 1. After the vehicle analysis, it was concluded that the main dummy injuries were caused by the deceleration pulse. In both PDB tests the passenger compartment was stable and negligible intrusions were measured. Therefore, we can conclude that no injury was caused by intrusions.

In general, we can state that higher dummy injuries will be caused by the deceleration pulse and will occur at the time of maximum B-Pillar deceleration. As shown in the dummy results comparison, high injuries were recorded in the Supermini 2 compared to the SUV 1, which also achieved a higher deceleration pulse

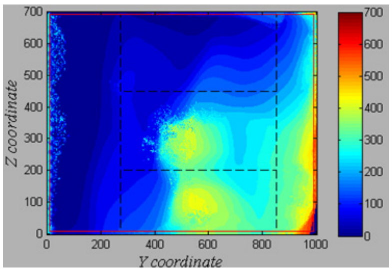
It has to be taken into account that all tested vehicles are equipped with different restraint systems that have developed for the R94 and Euro NCAP test conditions. The Supermini 2 is equipped with a double seatbelt pre-tensioner and knee airbag, while a single pre-tensioner an no knee airbag is available in the SUV 1, however better results were obtained in the SUV 1 crash test.

As the PDB test represents a more severe test for the Supermini 2 compared to the Euro NCAP one (conclusion from vehicle pulse analysis) high injury values were obtained in the PDB compared to the test performed by Euro NCAP, 12.6 and 15.1 points [Euro NCAP 2013], respectively.

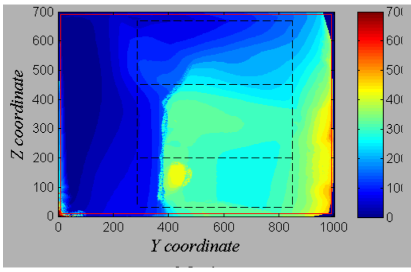
The PDB scanning was also analysed in order to evaluate the structural interaction of the vehicle (load spreading)

3.1.4 PDB Scanning

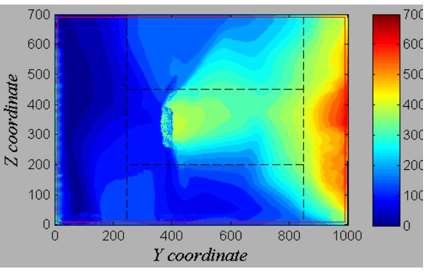
The PDB will serve to investigate the level of partner-protection provided by the tested vehicle. In particular, the PDB assessment will focus on load spreading issues. This structural interaction issue has been identified by the FIMCAR consortium as a Priority 1 issue. The PDB scans obtained in WP2 were included in the development of the PDB metrics.



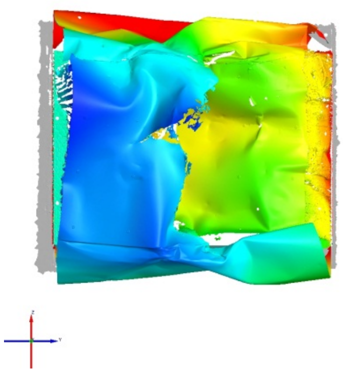
City Car 1



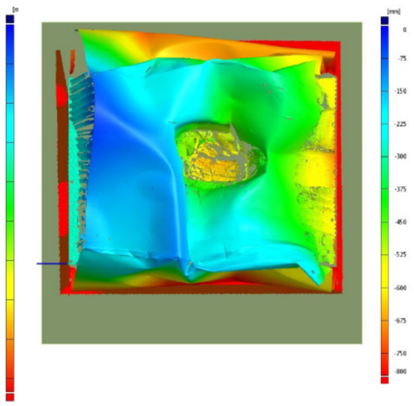
Supermini 2 at FIAT



Supermini 1



SUV 1



SFC 1

Figure 3.7: PDB scans.

The further development of the PDB metric can be found in Section 4.1 of this report. The development will focus on the load spreading metric between the longitudinals which has been defined as Priority for FIMCAR project.

3.2 Car-to-Car Tests

Three series of car-to-car crash tests will support the off-set assessment proposal and the PDB metric (PASS/FAIL definition) proposed by WP2 and will also support the final validation of the PDB metric, the test series are:

- Supermini 2, aligned and misaligned
- Supermini 1, aligned and misaligned
- SUV 1 vs. SFC 1, aligned and misaligned and SUV 2 vs. SFC 1 aligned

The main issues to be addressed in these car-to-car series are the underride/override issue, evaluated in the comparison between aligned and misaligned situations. The fork effect can be analysed in the aligned conditions, where no underride was present.

The compatibility issue is detected when one of the two tested vehicles will be performing poorly compared to the opposite vehicle, when the collision partner is an identical model, or a reference test. For the FIMCAR project a reference crash for the car-to-car tests was the Euro NCAP test results.

Supermini 2 showed a compatible situation in both aligned and misaligned car-to-car tests, details can be found in FIMCAR report D6.1 (Car-to-Car test results) [Sandqvist 2013]. Therefore, the Supermini 2 test series suggests that the tested vehicle should be a clear PASS the load spreading metric.

In the Supermini 1 case, the aligned car-to-car test presented acceptable results for both tested cars. On the other hand, the misaligned situation showed a bad performance in the lowered car compared to the other vehicles (aligned and raised), which was identified as an “incompatible” situation. High injuries for the diver and high vehicle intrusions were measured (single vehicle in all car-to-car test series with A-Pillar intrusions above 50 mm). The main issue observed in this misaligned situation was the underride of the raised vehicle into the lowered one, refer to D6.1. However, the “compatible” situation spotted in the aligned Supermini 1 and the underride situation in the misaligned suggests that the Supermini 1 should PASS the load spreading metric.

The PEAS of the Supermini 1 worked well in alignment conditions. Therefore, the Supermini 1 should PASS the metric. The absence of SEAS, or other structures to support vertical load spreading, can be identified as the main issue causing the “incompatible” situation in the misaligned test.

Finally, the last car-to-car test series showed better results in the SUV 1 vs. SFC 1 (aligned and misaligned) compared to the SUV 2 vs. SFC 1 (aligned), this last test was classified as an “incompatible” situation. The main reason for this “incompatible” situation observed in the SUV2- SFC 1 tests seems to be a fork effect.

In conclusion, the SUV 1 will be a clear PASS vehicle, while the SUV 2 and SFC 1 need to be further evaluated in order to understand the final reason of the fork effect and the main responsible of the “incompatible” situation.

4 FURTHER DEVELOPMENT OF PDB PROTOCOL

The fundamentals of the assessment method using the PDB off-set test have been defined in D2.1 [Lazaro 2013]. However, because the metric still needs to be developed further and validated, the majority of the FIMCAR members decided to propose the current ODB test procedure for the FIMCAR test approach.

It should be noted that work to develop compatibility metrics for the PDB test continued within the project because the majority of FIMCAR members believe that the PDB test has potential for compatibility assessment in the longer term.

4.1 Further Development of Metric

Different metrics assessing the depth of barrier deformation and distribution of deformations have been investigated in FIMCAR. During the initial development phase of the PDB metric, the development was supported by a database of 37 PDB tests at 60 km/h, tests performed in previous research projects (e.g. VC-Compat). WP2 has contributed to this database with 7 additional tests. Therefore, a total 44 cases were available to develop this metric.

The barrier deformation of these tests was analysed and taken as a reference for metric development. In a first stage, the barriers were classified following a subjective approach, gathering the barriers that suggest a good performance in compatibility, a detailed explanation about the subjective classification can be found in FIMCAR deliverable D2.1 [Lazaro 2013].

The PDB methodology consists of assessing the barrier deformation. The PDB vertically divided in zones as shown in Figure 4.1.

The area for assessing the PEAS has been identified as the priority for evaluating the load spreading (first priority in the evaluation).

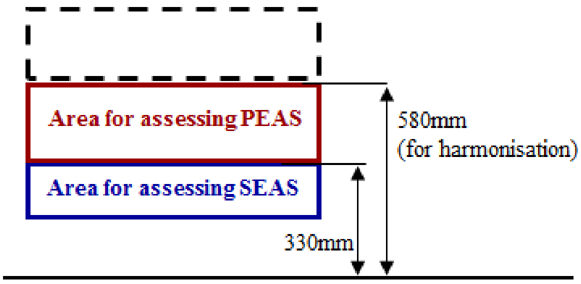


Figure 4.1: PDB areas of assessment.

This assessment area should include the common interaction zone (CIZ) of Part 581 (406 to 508 mm from ground). With this objective WP2 has defined different options for the load spreading evaluation. The 330 to 580 mm from ground area has been harmonized with the FW methodology. This area also includes the CIZ of Part 581.

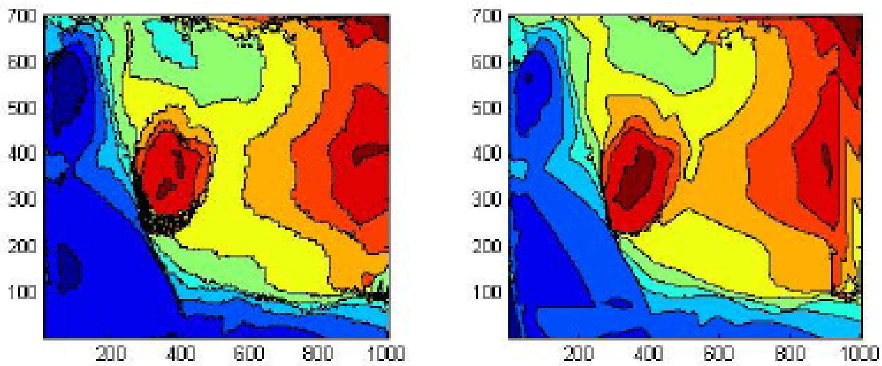
The PDB metric calculations follow the steps:

- PDB scan: *.stl file as the result
  - The deformation of the PDB barrier is digitized into a graphic file using the .stl format

- PDB scanning pre-processing: Two methods investigated "Ray Tracing" (VTI) and "Deformation Projection" (TNO)
    - The Ray Tracing procedure is used to address the potential for barrier folding and pockets in the deformed barriers. Ray Tracing uses the deepest deformed points when more than one surface in along the x axis is encountered for the same y&z coordinates.
    - Deformation Projection was a procedure to convert all x coordinates into an orthogonal y&z coordinate system. This procedure was part of the Ray Tracing procedure and not required as a separate procedure. Details of the methods are provided below.
- Criteria calculation: Load path detection and Load Spreading characteristics
    - The objective values calculated from the barrier deformations were reviewed and compared to the subjective calculations. Different criteria were developed and a summary is provided in Section 4.1.2
- Metric calculation: PASS/FAIL threshold definition

Different scan methodologies have been used in FIMCAR project. Details of the PDB scan comparisons using these methodologies are described in section 5.2.2 of this report.

Different pre-processing methods have been investigated in FIMCAR. Figure 4.2 shows an example of PDB scan pre-process using the "Ray Tracing" method (right image of Figure 4.2) and the "Deformation Projection" method (left image of Figure 4.2)



Deformation Projection Ray Tracing

Figure 4.2: PDB pre-processing methods.

As shown in Figure 4.2, both pre-processing methods, present reasonably consistent results for deformation. The Ray Tracing procedure developed at VTI provided a more consistent filtering of the data and made metrics based on deformation gradients less susceptible to small (under 3 mm) tears or folds. After the confirmation that both presented methodologies provided similar results, VTI method was adopted for further PDB analysis.

Different scanning methodologies have been used in FIMCAR project. Both laser scanning and photographic methods were used. The results of the PDB scan comparisons are given described in Section 5.2.2 of this report.

4.1.1 Load Path Detection (Longitudinal Deformation)

The aim of the criteria is to identify front-end structures, which are able to deform the barrier in a significant manner. The load path will be evaluated by the barrier deformation. The 3D measurements of the barrier will allow the identification of the vehicle load paths.

The load path detection will be assessed by the Longitudinal Deformation of the barrier. The Longitudinal deformation (d) criterion has been developed using statistical characteristics of the deformation within a defined zone, taking coefficients of the barrier longitudinal deformations.

The parameter and limits can also be used to limit the front-end stiffness controlling the maximum deformation of the barrier. Proposals for this criterion were presented in FIMCAR Deliverable D2.1 [Lazaro 2013]. Due to the priority of compatibility issues in the FIMCAR project (Figure 3.1) no further investigation was carried out for stiffness matching during the final development phase of the PDB protocol.

4.1.2 Load Spreading

The aim of this criterion is to assess the load spreading characteristics of a specific load path. This criterion is identified as a key issue for FIMCAR. Therefore, its development is particularly important for the project. Several different concepts were explored and evaluated in the second half of the project.

4.1.2.1 Maximum Sub-zone Displacement

One approach to load spreading used the area of investigation for horizontal load spreading divided horizontally in a total of N equal sub-zones as shown in Figure 4.3. The vertical limits of overall area will be fixed (e.g. 330 to 580 mm from ground). The horizontal limits and in consequence the final size of the sub-zones will differ in function of the width of the vehicle.

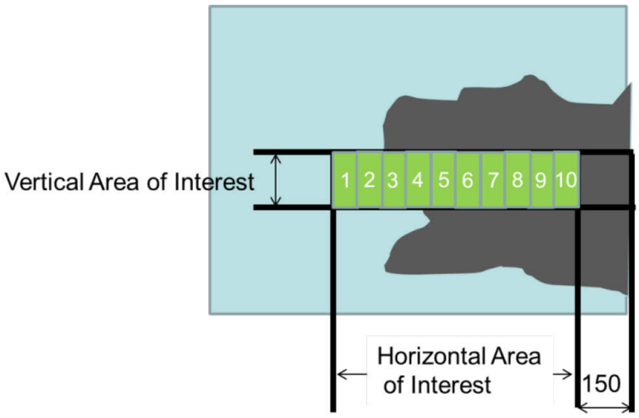


Figure 4.3: Subzone definition.

Dividing the area of analysis in sub-zones allows investigating the horizontal load spreading over the total area of investigation. Further analysis of the sub-zones has been done in terms of differences of the longitudinal deformations among the different sub-zones.

Different parameters can be calculated from these N sub-zones:

- D is the average of longitudinal deformation of the complete area
- Di (i=1 to N) is the average of longitudinal deformation for the i sub-zone
- q%ile i (i=1 to N) is the q%ile of longitudinal deformation for the i sub-zone

Several criteria have been developed and investigated using the above mentioned parameters, some examples are:

- D/Di gives an estimation of the horizontal variation of the i sub-zone compare to the total average
- ei=D-Di is the deviation of a sub-zone from the overall average of deformation

Vehicles that have a good horizontal load distribution should have similar deformations in each sub-zone. Therefore criteria that promote small deviations among the subzones should promote better structural interactions.

4.1.2.2 Change in Horizontal Slope – Digital Derivative Y

Good horizontal load distribution should produce an even distribution of PDB deformation across the width of the vehicle. One indicator of the load spreading should therefore be the absence of sudden changes in the slope of the barrier deformation in the lateral direction. If one considers the average depth at every horizontal segment of a barrier deformation within the assessment area as shown in Figure 4.4, the deformation vs horizontal position graphs can be plotted as shown under the PDB deformation plots. The displacement graphs can be further processed so that each horizontal position is associated with the slope in of deformation in the y direction. The Digital Derivative in Y (DDY) is an indicator to how smooth the barrier is deformed. Figure 4.4 (left side) shows an example of a relatively smooth barrier deformation with few abrupt displacement changes while the right side of Figure 4.4 indicates more localised deformations and thus poor horizontal load spreading.

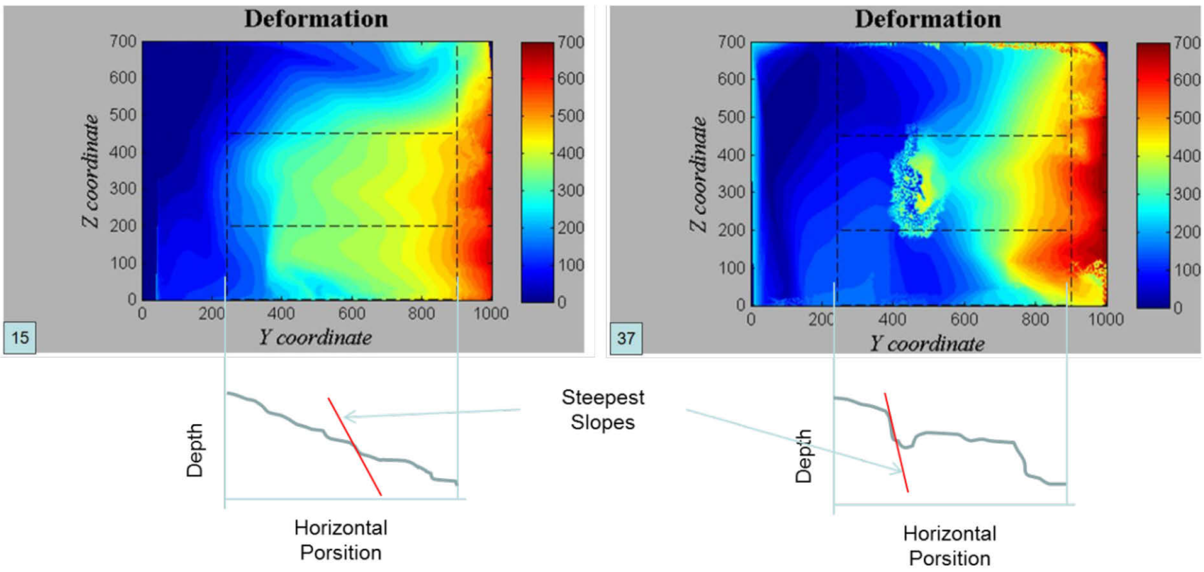


Figure 4.4: Horizontal slopes.

The DDY metric

During the review of the results, the DDY calculation over the entire horizontal area of investigation emerged as the best candidate to evaluate the Load Spreading issue. This parameter guarantees the independency of the metric to the vehicle mass. At the same time, it represents a relatively easy approach as no need of additional divisions of the assessment area is necessary.

$$\text{For } y=1 \text{ to } N_y,\ z=1 \text{ to } N_z \quad DDY(y,z) = \left|\frac{X(y,z)-X(y-1,z)}{\text{mesh size}}\right|$$

Equation 4.1: DDY equation.

Regarding the metric development different options were investigated:

- Lateral limit: UTAC proposal (W/2-100mm), 80%, 70% and 60% of vehicle width
- Vertical definition: CIZ of Part 581 and Row 3&4
- DDY criteria: max DDY, 99%ile DDY and standard deviation of DDY
- Mesh dimensions: 1,3,5,10 mm

The 99%ile DDY calculated in the defined area gives an estimation of the homogeneity of the barrier. Lower values will correspond to small variations in the analysed area, therefore more homogeneous vehicle deformation.

Figure 4.5 summarizes the lateral limits of the area of investigation, which is fixed at 150 mm from the centre of the vehicle and extends laterally to the side of the tested vehicle. These dimensions are constant for left-hand or right-hand drive cars.

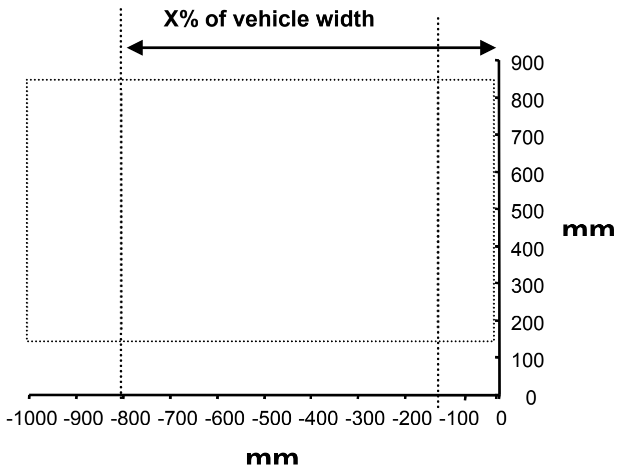


Figure 4.5: Lateral limits.

The assessment areas consisting of 330-580 mm (Row 3&4 in the FW test), 60% vehicle width and 99%ile DDY provided the best correlation with the subjective classification and showed acceptable R&R results. Figure 4.6 shows the subjective classification as described in FIMCAR Deliverable D2.1 [Lazaro 2013] against the 99%ile DDY criterion in the evaluation area (Row 3&4 and 60%). The subjective classification grouped the studied cases in three different groups. These groups identify different horizontal load spreading cases due to the architecture and can be summarised as:

- G1: Group 1, Cases that should PASS a horizontal load spreading metric
- G2: Group 2, Borderline cases that required a specific evaluation
- G3: Group 3, Cases that should FAIL a horizontal load spreading metric

It is important to note that Figure 4.6 shows the initial analysis results as described in the original FIMCAR Deliverable D2.2. However, in the review process it appears that some results are incorrect. The updated results are shown in Chapter 4.6 below.

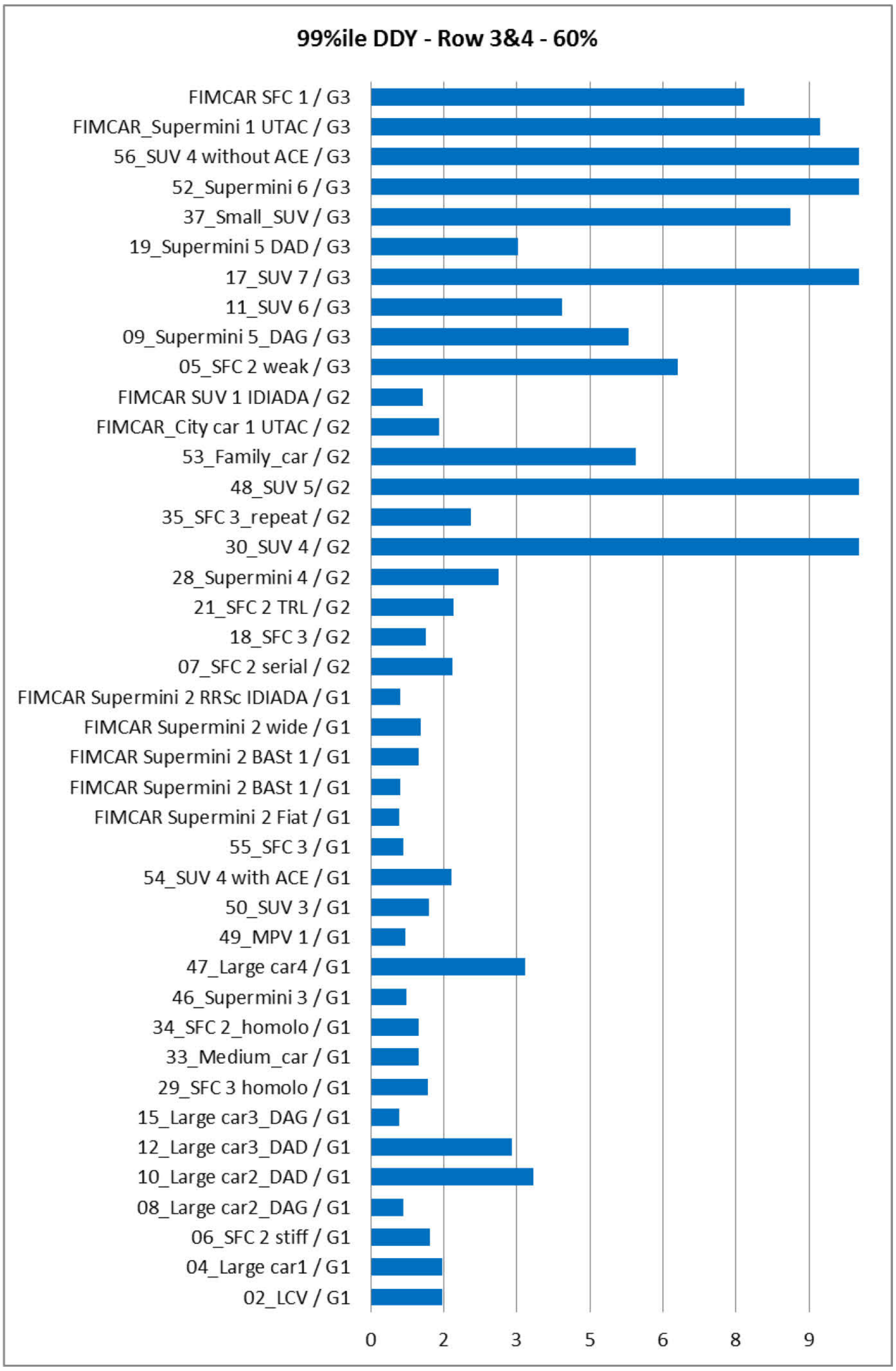


Figure 4.6: Initial 99% DDY, Row 3&4, 60%.

The results were analysed and the following cases were investigated for the 99%ile DDY criteria.

- <u>PASS/FAIL threshold must be consistent with subjective classification.</u>

The 99%ile DDY criterion with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern, G1, and barrier with localised holes, G3. There were some borderline cases that should be reviewed but the criteria had a good sensitivity to discriminate vehicles according to the subjective rating.

- <u>Repeatability in terms of value for the R&R study in WP2 (Supermini 2).</u>

The criterion showed a good repeatability for the different tests of the Supermini 2, values around 0.60, well below the proposed limit. This confirms the good performance expected by the FIMCAR Supermini 2.

- Additional R&R of previous projects, only PASS/FAIL.

An acceptable R&R in terms of PASS/FAIL assessment was found for the cases studied in previous projects. All R&R cases for previous projects showed the same PASS/FAIL result, except the left and right hand versions (Case 9 and 19 in Figure 4.7) for one vehicle. In one case the hole was smoother that the other and as a consequence one passes the metric and the second fails. This difference arises due to the asymmetric drivetrain structures in the vehicle and should be considered in a “worst case” condition for testing.

- Studies of “modified” vehicles also taken into account.

The proposed metric also showed a consistent result in the “modified” vehicles studies. Vehicle 54 was a redesign of vehicle 56 for compatibility and the modifications introduced in the vehicles were reflected by the metric and correlated with the PASS/FAIL results.

4.1.3 Conclusions

The structural interaction has been defined as a main issue for improving the partner-protection of a vehicle. The vertical location of the load paths, assessed by the longitudinal deformation of the barrier, can provide an estimation of the risk that the tested vehicle will be interacting with the opponent car. However this is better addressed in the structural alignment metric in the FWDB test [Adolph 2013].

The contribution of the SEAS has been defined as an added value to contribute in partner-protection issues. In the first stages of FIMCAR, 50 to 65% of longitudinal deformation, or mean deformation, have been identified as the most promising parameters to detect the load paths [Lazaro 2013]. This metric was not further investigated as the priority for the last year in FIMCAR was to develop a horizontal load spreading criterion.

The load spreading in the CIZ has been also identified as a main issue to be addressed by the PDB procedure. Several proposals for assessing the characteristics of the load spreading have been investigated in FIMCAR. The criterion with the best correlation to subjective vehicle ranking has been obtained using the slope of the deformations in the Y direction. The assessment parameter is the 99%ile DDY calculated in the Row 3&4 investigation area and with an outer vertical limit of 60%. The Row 3&4 area is harmonized with the FW metrics, while the 60% of the vehicle width ensures the involvement of a significant part of PEAS in the assessment. This assessment width captures the crossbeam performance between the longitudinals for European cars.

The objective of this criterion is to address compatibility issues like the small overlap and the fork effect.

4.2 Artificial PDB Profiles

The evaluation of the PDB assessment metrics was initially carried out by the deformation patterns coming from PDB and MPBD crashes. The subjective analysis enabled the FIMCAR group to distinguish between clear effects like holes and homogenous footprints. The result of this process was the subjective classification of the tested vehicles into three groups, see

FIMCAR Deliverable D2.1 [Lazaro 2013]. However, sometimes the metric results were not clearly understood and it was assumed that the combination of different compatibility characteristics were interpreted differently in the metrics than in the subjective assessment. In particular the BDA software provides one value containing the assessment of different characteristics like maximum intrusion depth and homogeneity intrusion depth in specific areas. In order to separate different characteristics (i.e., intrusion depth, number of load paths, homogeneity and deformed areas that are within investigations zones and those that exceed the investigation zones) independently, artificial deformation profiles were developed. The main objective was to create simple deformation patterns addressing the following specific frontal impact compatibility issues of the PDB:

- Intrusion depth
- Vertical load spreading
- Horizontal load spreading
- Homogeneity (in terms of proportion of deformed area within a specific area)

Based on a re-meshed cladding plate of the FEM PDB model, 47 artificial profiles where created. In addition to the evaluation of the BDA software the most promising assessment metrics developed within FICMAR (Homogeneity Value and Smooth Deformation Index - SDI), see [Lazaro 2013], and DDY were analysed too. A summary of all artificial profiles and the corresponding assessments is shown in Annex F.

The following analysis is based on the artificial profiles shown in Annex F. Qualitative information about the geometry and the assessment by BDA software, Homogeneity value and DDY can be found there. It is important to know that the DDY metric was developed relative late in the project and that this metric addresses only the homogeneity within a specific area (Area of Interest – AoI). The artificial profiles were not designed to address this kind of homogeneity. That is why the DDY assessments alter between 20.1 and 0.0 depending on whether or not the deformation is within the AoI. Thereby 0.0 means that the deformation is completely within the AoI and 20.1 indicate that the deformation exceeds the borders of the AoI. Therefore the DDY values are not taken into account in the following analysis. As a result of this it needs to be stated that the DDY metric needs to be improved to better cope with deformation profiles that exceed the AoI as homogeneity exceeding the width of the longitudinals was considered to be important for small overlap compatibility.

The visualisation of the assessments of BDA software and Homogeneity value is given in relation to the mean value of the corresponding group. This means that values > 1.0 indicate increasing scores and values < 1.0 indicate decreasing scores. The BDA software assessment uses the Partner Protection Score (PPS) which is a combined rating for all frontal impact compatibility issues listed above. The higher this value, the better is the assessment of the compatibility. The Homogeneity value is intended only to address the homogeneity of the deformation within the AoI. The higher the Homogeneity value, the more homogenous is the deformation pattern.

4.2.1 Sensitivity Analysis – Intrusions

The intrusion depth should not have an influence on the homogeneity assessments. The main reason is that heavier vehicles generally produce deeper intrusions than lighter vehicles even though they can have comparable load spreading. If the assessment results strongly depend on the vehicle mass, the corresponding metric needs to be revised because on the one hand it is very difficult for light vehicles to create a specific intrusion depth and for heavy vehicles it could be a problem to reduce the maximum intrusion depth. Figure 4.7 are examples of identical PDB profiles except for deformation depth and Figure 4.8 are the resulting evaluations.

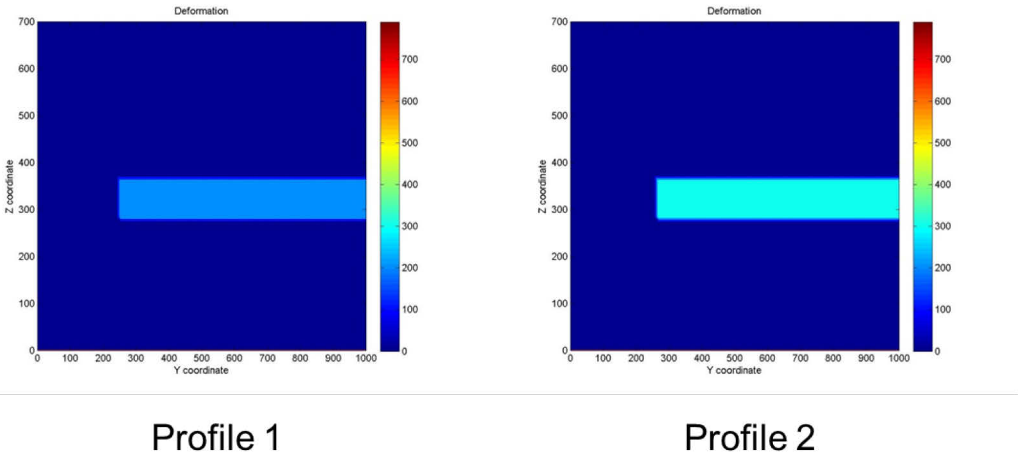


Figure 4.7: Intrusion depth – variation of the maximum intrusion (300mm to 400mm) within the middle area of the PDB (only minor differences are expected).

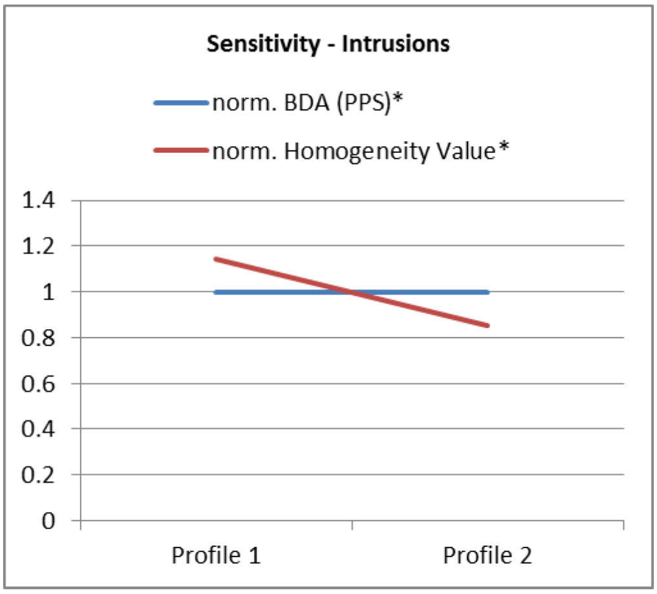


Figure 4.8: Dependency on intrusion depth of PDB metrics.

According to the assessment corridors for intrusions into the PDB (see [Lazaro 2013]) which were initially defined for the first assessment metric proposed by UTAC, the results show no dependency on the intrusion depth because both values are within the range of maximum rating. A comparison with other artificial profiles show (e.g. Profile 7 and Profile 38 in Annex F) that the scoring of the intrusions works correctly and the scoring changes in dependency on the computed values. However, the Homogeneity value also changes, even though the deformed area does not, which indicates a dependency on the intrusion depth too.

4.2.2 Sensitivity Analysis – Vertical Load Spreading

Vertical load spreading within LCW Row 3 and Row 4 (330 mm to 580 mm above the ground) is mainly addressed by the FWB test procedures. Additionally the assessment of forces in Row 2 (205 mm to 330 mm above the ground) takes lower load paths into account. While the analysis of loads applied to the LCW is restricted by the relative rough resolution due to the load cell array, the PDB offers the potential to analyse the deformation continuously. Furthermore the whole front of the PDB is theoretically capable to be analysed. Thereby the area can be divided into sub areas which correspond e.g. to the rows of the LCW. The assessment metrics should be able to distinguish between the impacted areas shown in Figure 4.9. In terms of the BDA software there are assessment corridors defined addressing the intrusion depth in the upper, middle and lower area of the PDB. Depending on the impact location and the intrusion depth the PPS should vary. The Homogeneity value only addresses deformations in the middle and lower area. A further criterion is the vertical load spreading within the area of LCW Row 3 and Row 4. Because the FWB cannot precisely detect the impact location within Row 3 and Row 4 the PDB should be able to provide information about the vertical load spreading within this area. Figure 4.10 shows how both metrics are detecting differences in when the lower load path is present with the Homogeneity Value being more sensitive to the presence of the lower load path.

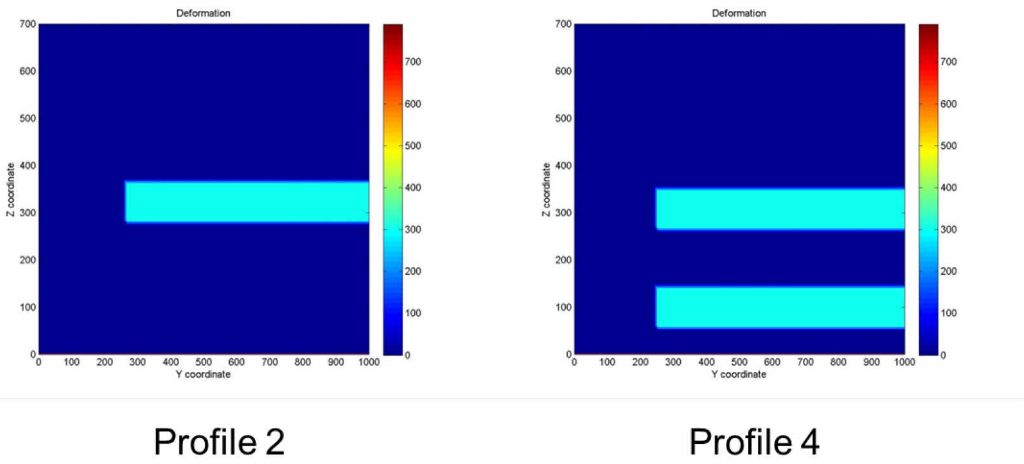


Figure 4.9: Vertical Load Spreading – variation of the impact location, only middle area (left), middle and lower area (right) (Profile 4 should be rated better than Profile 2).

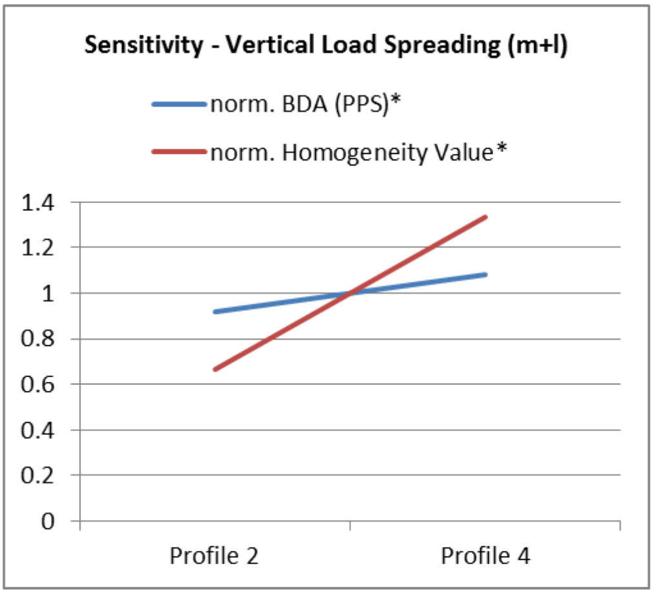


Figure 4.10: Dependency on vertical load spreading in middle and lower area of PDB metrics.

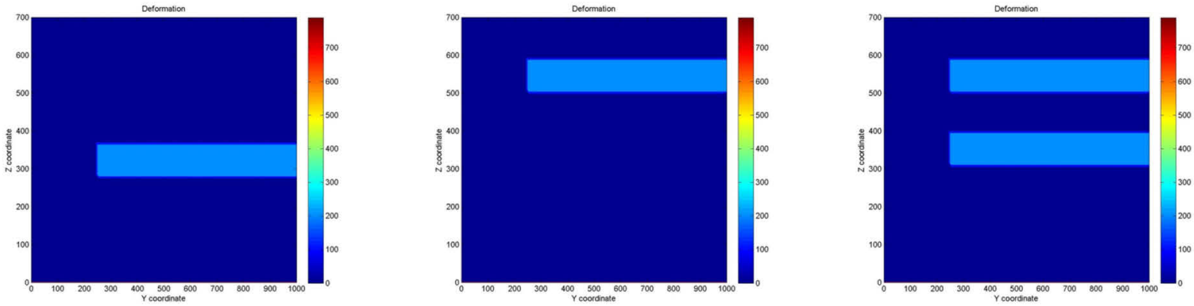


Figure 4.11: Vertical Load Spreading – variation of the impact location, only middle area (left), only upper area (middle), middle and upper area (right) (Profile 34 should be rated worst because load spreading is mainly required in the middle area and below).

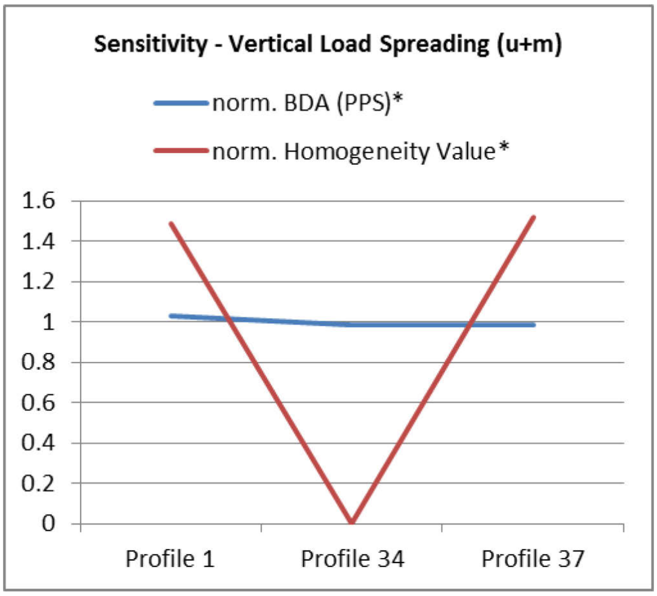


Figure 4.12: Dependency on vertical load spreading in middle and upper area of PDB metrics.

The artificial profiles clearly show that the Homogeneity value does not take into account the upper area, see Figure 4.11and Figure 4.11. Furthermore the same deformation in the middle area and additional deformation in the lower zone, see Figure 4.9 (Profile 2 and Profile 4), leads to a better assessment by the Homogeneity value Figure 4.10, because the intrusion depth within the lower area is only one part of the combined assessment criterion of the BDA software and thus the effect on the total PPS score is relative small compared to the Homogeneity value. The reason for the identical assessment of Profile 34 and 37 by the BDA software is that the homogeneity of Profile 34 is assessed with the maximum score while the deformation of the middle area results in zero points. In total the PPS value of both profiles is the same.

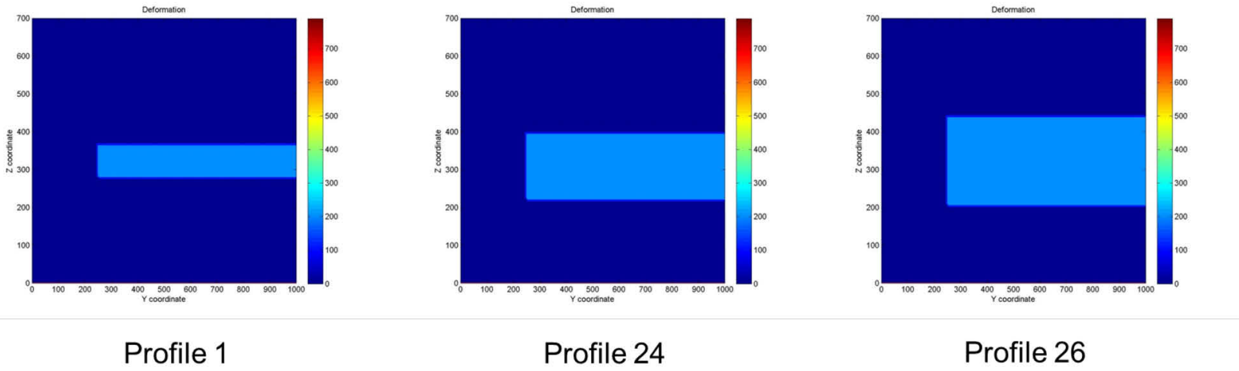


Figure 4.13: Vertical Load Spreading – variation of the impacted area within the LCW Row 3 and Row 4 (rating should improve from left to right).

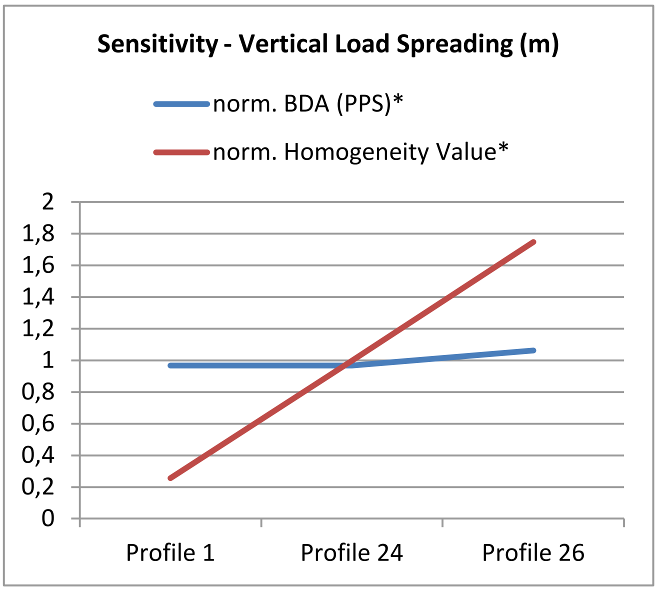


Figure 4.14 Dependency on vertical load spreading within the LCW Row 3 and Row 4 of PDB metrics.

Figure 4.14 shows a clear trend for the homogeneity value. The more area of LCW Row 3 and Row 4 was deformed (Figure 4.13), the better the Homogeneity assessment. The BDA software shows no clear dependency on the deformed area. The increased PPS for Profile 26 seems to be a result of a better assessment of the homogeneity within the middle area. In that case the deformed area exceeds the vertical borders because the middle area assessed by the BDA software (350 mm to 600 mm above the ground) does not corresponds to the

LCW grid (330 mm to 480 mm above the ground). This seems to affect the calculation of the TV value (which is used for both metrics) positively because the size of the deformed assessed area is larger.

4.2.3 Sensitivity Analysis – Horizontal Load Spreading

As already mentioned the PDB was the only test procedure that offers the potential to assess the horizontal load spreading. All other discussed test procedures and corresponding horizontal load spreading metrics were not able to assess the horizontal load spreading in an appropriate manner. The BDA software and the homogeneity value do not distinguish between the direction of load spreading (vertically or horizontally). However, if the intrusion depth is constant, an increasing horizontal size of deformation should affect the compatibility metrics positively. If the number of load paths is increased laterally, as in Figure 4.15, there is not a strong correlation between the area and metric output, Figure 4.16.

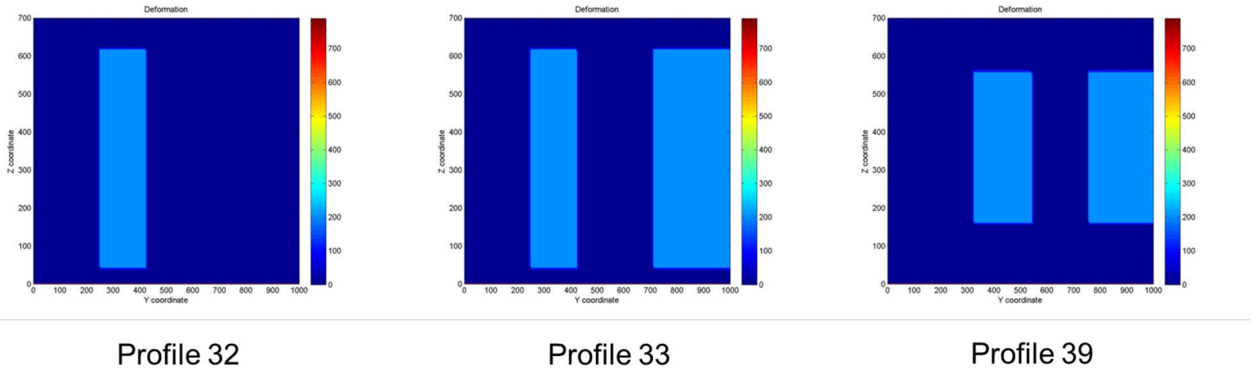


Figure 4.15: Horizontal Load Spreading I – variation of the impact location in upper, middle and lower area (Profile 33 should be rated best followed by 39 and 32).

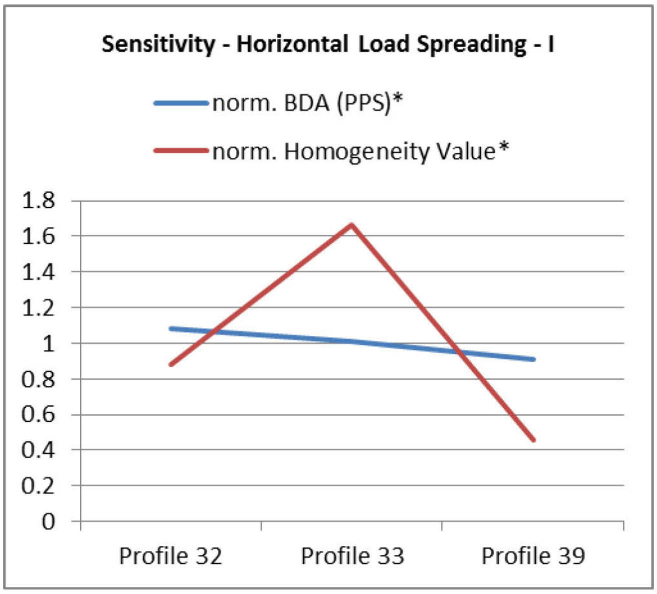


Figure 4.16: Dependency on horizontal load spreading in upper, middle and lower area of PDB metrics.

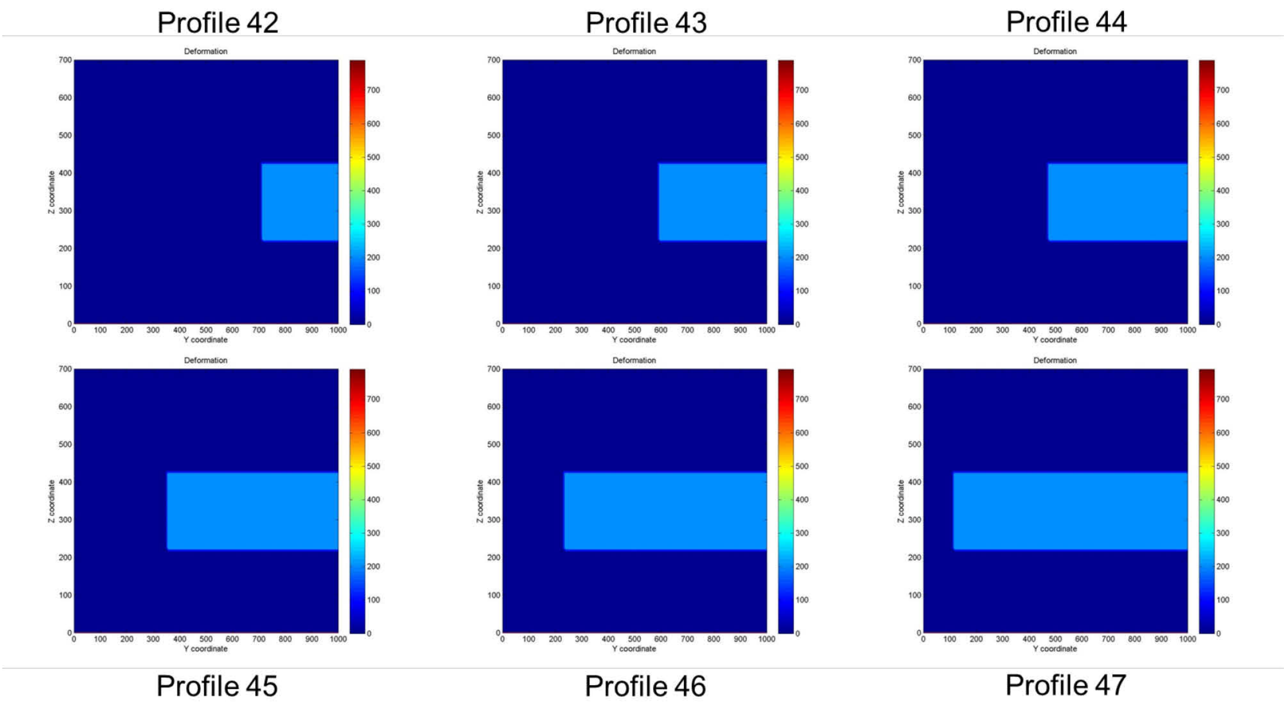


Figure 4.17: Horizontal Load Spreading II – variation of the deformed area within the middle area (rating should improve from left to right).

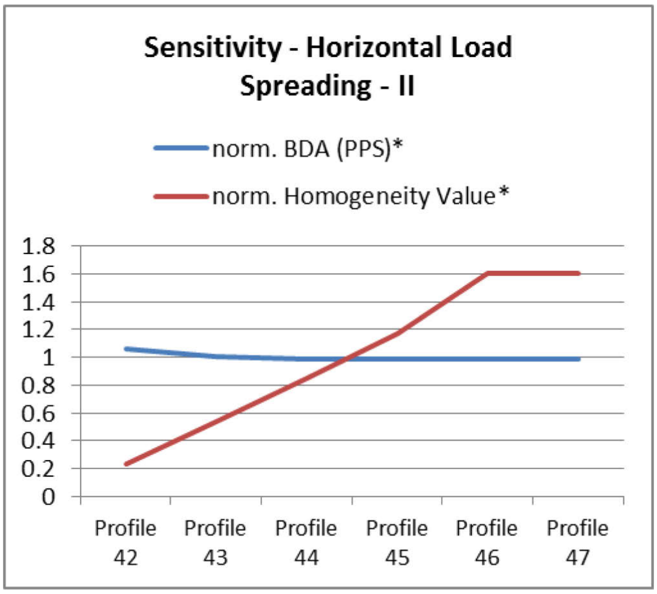


Figure 4.18. Dependency on horizontal load spreading within the middle area of PDB metrics.

These two examples (horizontal load spreading I and II) show the expected correlation of the deformed area and the Homogeneity value. The more area is deformed by one load path within the AoI, the better is the assessment. As expected, Figure 4.18 shows that increasing the area beyond the borders of the AoI results in a constant Homogeneity value. Regarding the BDA software assessment there is a poor correlation between deformed area and the computed PPS. The main reason for that behaviour could be the sensitivity of the TV value (used by BDA software to compute the homogeneity) to sharp edges. The more sharp edges, respectively, and the longer the sharp edges are, the higher is the TV value which results in poor assessment.

4.2.4 Sensitivity Analysis – Homogeneity

The homogeneity aspect should mainly address holes within the PDB which can be observed if the penetrating longitudinal is very stiff, due to the high vehicle mass or if the connection to other structures like cross beam or sub frame is not sufficient. As generally agreed, the presence of holes such as those found in Figure 4.19 is a good indicator of poor compatibility. For that reason the assessment metric should address this aspect and should be able to detect holes.

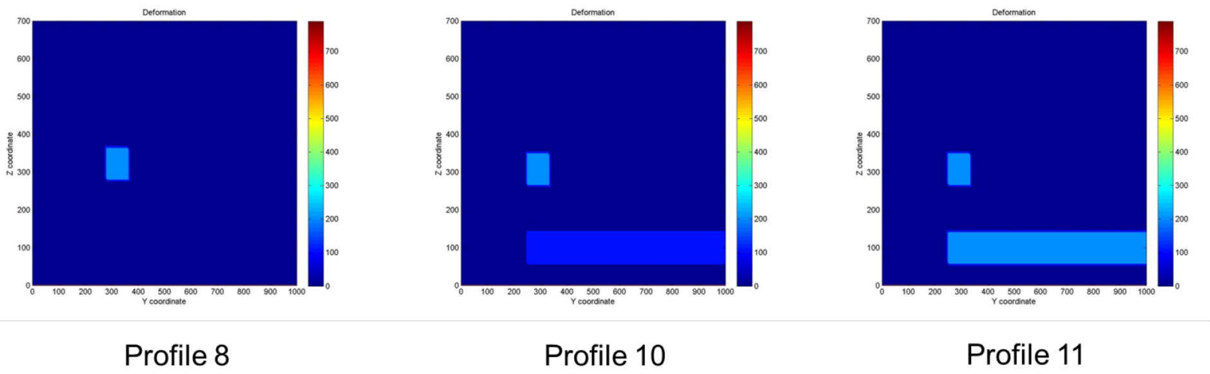


Figure 4.19. Homogeneity I – holes and variation of the deformed area within the lower area (Profile 8 should be rated worst, Profile 11 should be rated slightly better than Profile 10).

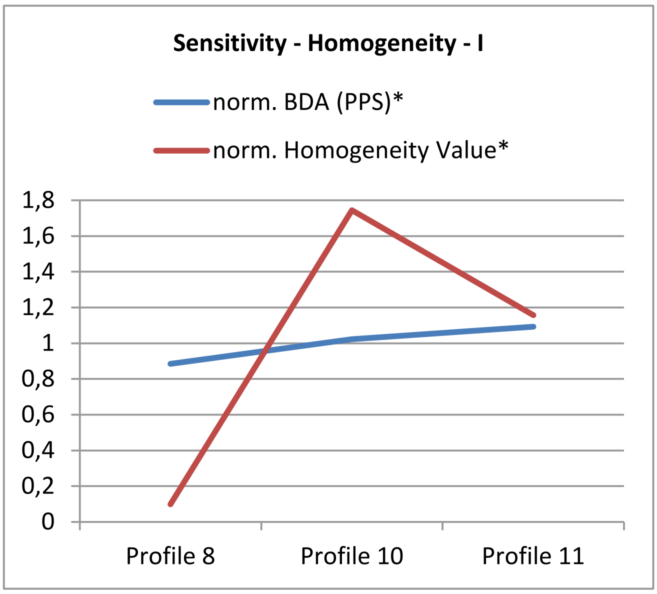


Figure 4.20: Dependency on holes and additional deformed lower area of PDB metrics.

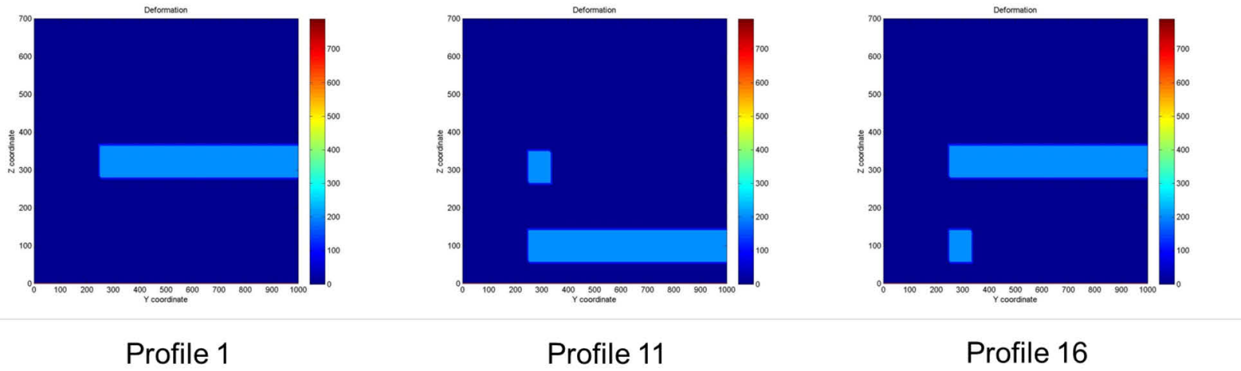


Figure 4.21: Homogeneity II – variation of the position of the hole (Profile 11 should be rated worst, Profile 16 should be rated similar to Profile 1).

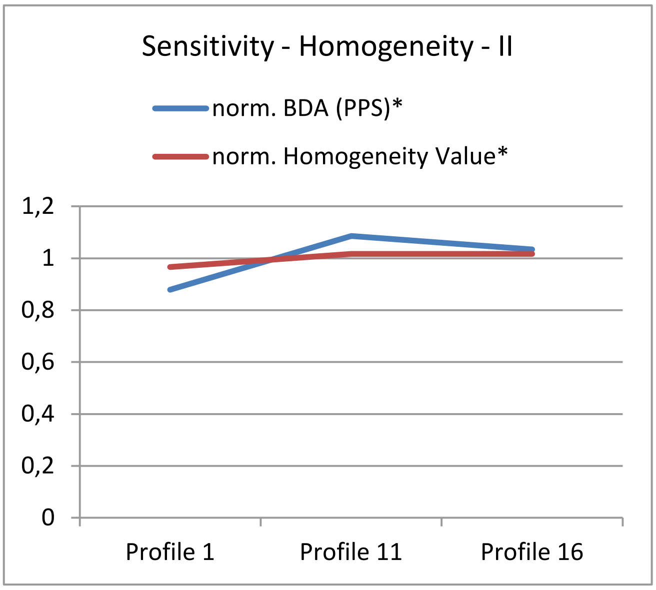


Figure 4.22: Dependency on the position of holes of PDB metrics.

The two examples based on Figure 4.19 and Figure 4.21 show contradicting results regarding the BDA software assessment. Figure 4.22 shows an increasing trend for the PPS for the profiles in Figure 4.21. But the reason for the positive assessment is the better rating of the deeper deformation in the lower area. The assessment will be worse if the influence of the intrusion depth is not eliminated (intrusion depth remains constant in Profiles 1, 11 and 16) and the main part of the deformation is within the middle area. This indicates again a problem of the TV value computation. The Homogeneity value also seems to be sensitive to the depth of the intrusion, because the Homogeneity value decreases see Figure 4.20. The Homogeneity value seems not to be sensitive to the location of the hole, see Figure 4.22 Therefore the metric cannot distinguish between the middle and lower area and if the hole is located in one of these areas.

Sensitivity Analysis – Vehicle Width

The analysis of the artificial profiles was conducted w.r.t. two different vehicle widths. The represented widths correspond to an average width of a small family car (average width = 1652 mm ➔ y_{min} = 274 mm) and an average width of an off road car (average width = 1842 mm ➔ y_{min} = 179 mm), see Figure 4.23.

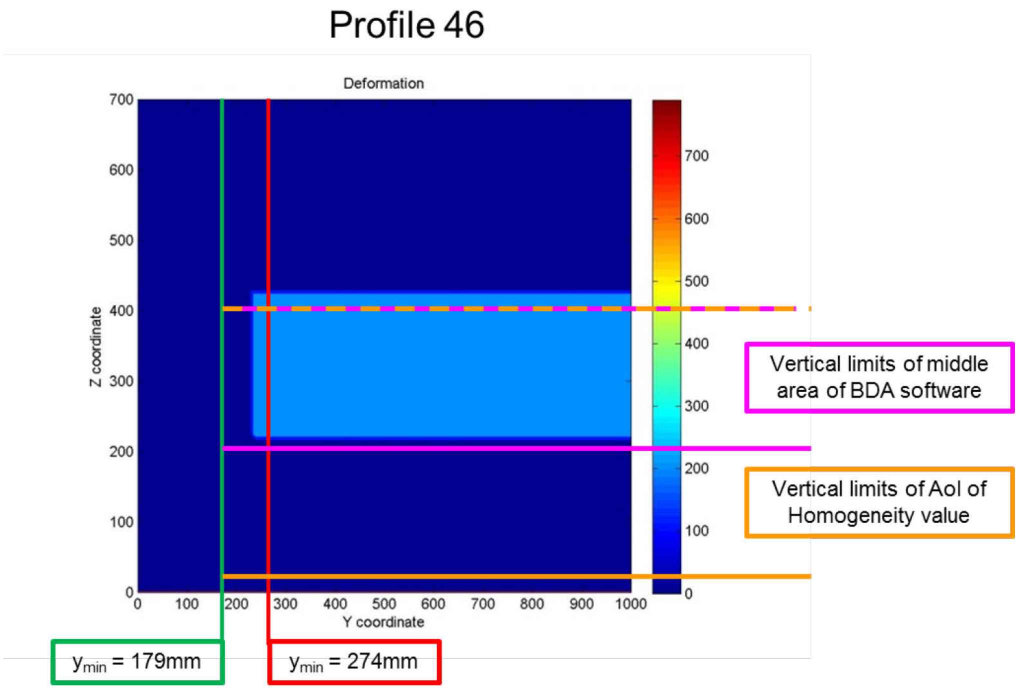


Figure 4.23: Different AoI depending on used vehicle width and assessment metric.

Regarding the constant deformation patterns of the artificial profiles, the assessments of the small family car should be better, because the deformations cover a larger proportion of the AoI than for the wider off road car. This should mainly have an effect on the homogeneity computation for Figure 4.23. In most of the cases the expected behaviour could be observed. However, regarding the assessments of Profile 42 to Profile 47, see Figure 4.24 unexpected results were computed.

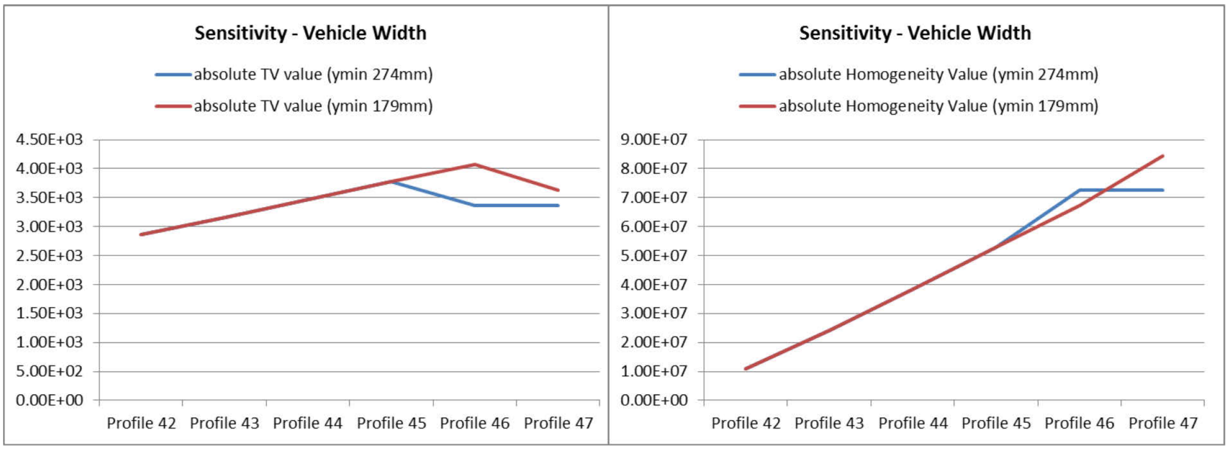


Figure 4.24: Absolute values for TV value (as part of the PPS) and Homogeneity value for different vehicle widths.

Figure 4.24 shows the trends of TV value (left) and Homogeneity value (right) for the two different vehicle widths. The main expectation was that the values are different depending on the vehicle width due to the changing AoI. This could not be confirmed. Both metrics compute the same values for Profile 42 to Profile 45. Profile 46 exceeds the limits of the AoI for the small family car (y_{min} = 274 mm). While the TV value decreases the Homogeneity value increases. This confirms former observations that the computation of the homogeneity in both metrics is interfered if the deformation exceeds the borders of the AoI.

4.2.5 Summary of Analyses of Artificial Profiles

Table 2 summarises the main findings of the analysis of the artificial profiles. Regarding these very simplified footprints, both investigated metrics seem not to be capable of addressing all compatibility issues. The main disadvantage is the dependency on the intrusion depth which is not acceptable because this indicates a relation to the vehicle mass. Another important factor is that both metrics were not able to detect holes. Although the Homogeneity value assessed holes worse, the metric could not distinguish where the hole was located because the metric used a combined AoI consisting of middle and upper area. However, an update of the principle seems to be possible to address this issue.

Table 2: Summary of assessment metric analysis of artificial profiles.

compatibility issue		expected behaviour	BDA software	Homogeneity value
intrusion depth		no dependency	-	-
vertical load spreading	upper and middle area	should be detected	+	-
	middle and lower area		+	-
	within the CIZ		-	+
horizontal load spreading			-	+
homogeneity (detection of holes)			-	-
horizontal load spreading in relation to vehicle width			-	-

„+" – expected behaviour confirmed „-" – expected behaviour not observed

The *artificial* profiles offered a good possibility to check the assessment metrics and to conduct sensitivity analyses. Thus it was possible to create footprints to address the specific compatibility issues and to check if the metrics assessment fits to the expected results. Prospective work should focus on the investigation of the DDY metric which could not be assessed with the created setup of artificial profiles. New created profiles should be used to improve the understanding of the homogeneity assessment and the hole detection

4.3 Analysis of PDB Model Deformation Pattern - Preparation of Numerical Simulation Output

The FIMCAR crash simulation programme was already described in FIMCAR Deliverable D2.1 [Lazaro 2013]. However, due to model quality issues at that time, the results were not available when D2.1 was finalised. However, before discussing the simulation results it is important to describe problems with the analysis of the PDB Model deformation.

The updated PDB model [Stein 2013/2] provided realistic deformation patterns especially in terms of material failure and lateral stiffness of the honeycombs. Due to the improved model sensitivity, analysis of structural modifications could be conducted. To assess the resulting footprint of the barrier the extraction of the cladding plate and (if needed) further parts, like the honeycomb, from the numerical output was necessary. Thereby an analogue procedure to the real scanning process was used to capture the deformations. However, even though the numerical PDB model was able to represent mechanisms like rupture of the cladding plate, the treatment of the crash solver to represent this behaviour lead to time consuming manual post-processing. The main reason is the treatment of material failure which is typically realised by deletion of individual elements in the area where rupture occurs or that the stress-strain calculation of these "deleted elements" is not further considered which can lead to unrealistic deformations of these elements, see Figure 4.25.

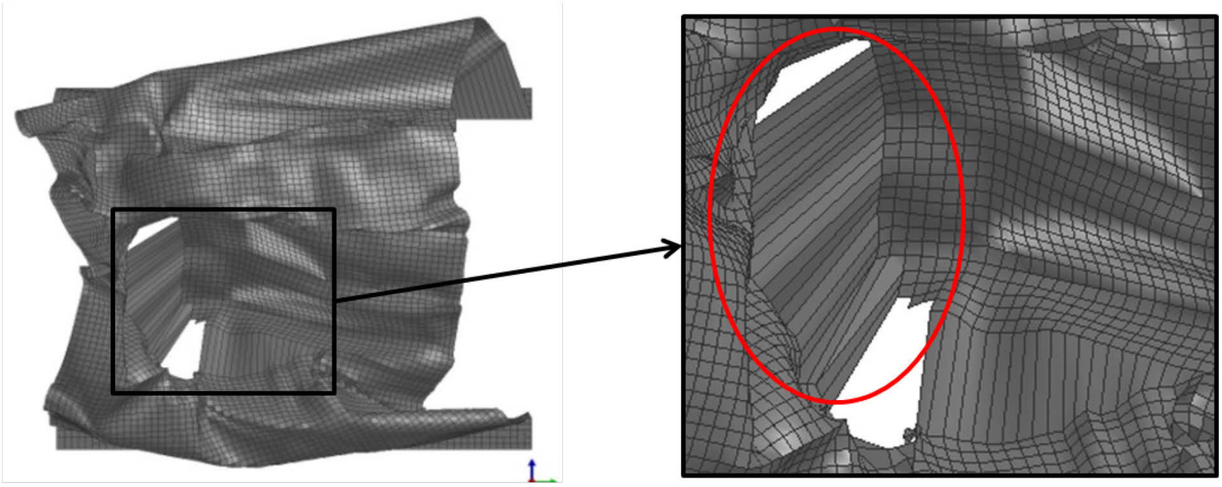


Figure 4.25: Unrealistic deformed elements due to material failure, because stress/strain calculation is not further considered.

In terms of the PDB model, the element elimination lead to the special case of "free nodes", if neighboured elements will be eliminated which share a common node, see figure 4.24.

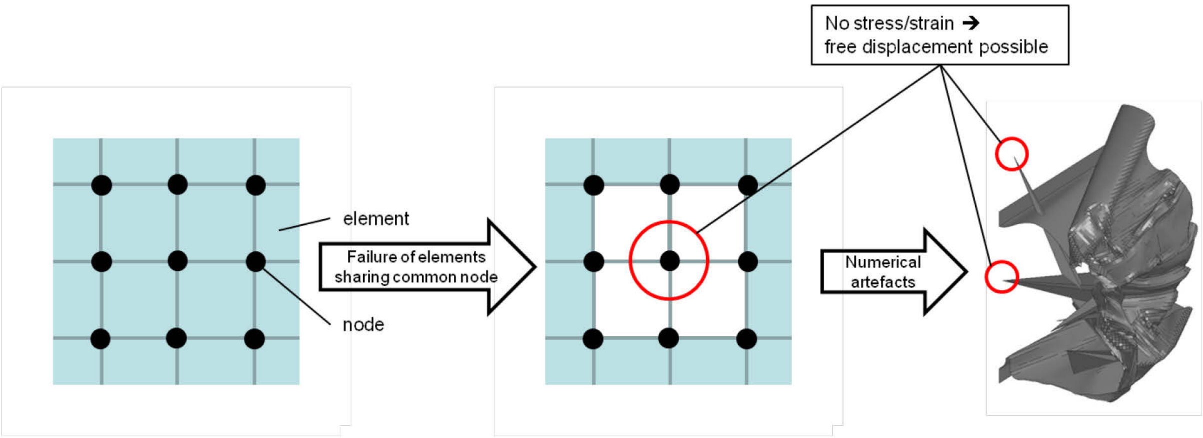


Figure 4.26: Creation of "free nodes" due to the treatment of material failure in the numerical PDB model.

These "free nodes" can move without any restriction because no reaction forces affect this node. This phenomenon can create numerical artefacts that complicate the post-processing. Figure 4.27 illustrates the magnitude of these numerical artefacts at the end of a simulation.

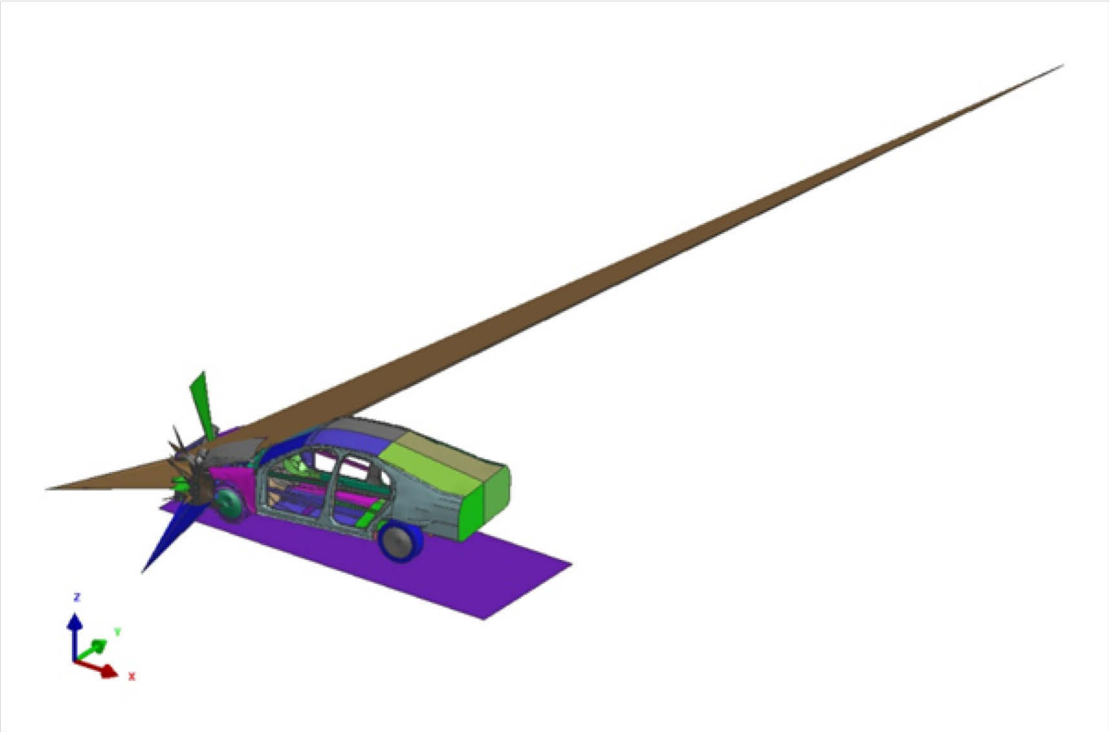


Figure 4.27: Large deformed elements at the end of the simulation due to material failure treatment.

Typically these elements and nodes are not taken into account in the post-processing. For the analysis of the barrier footprint the location of the nodes are crucial because they will be used to create the final STL file of the deformed cladding plate. Therefore a manual cleaning process is necessary to remove these nodes from the data and to prepare the output for the following assessment, see figure 4.26.

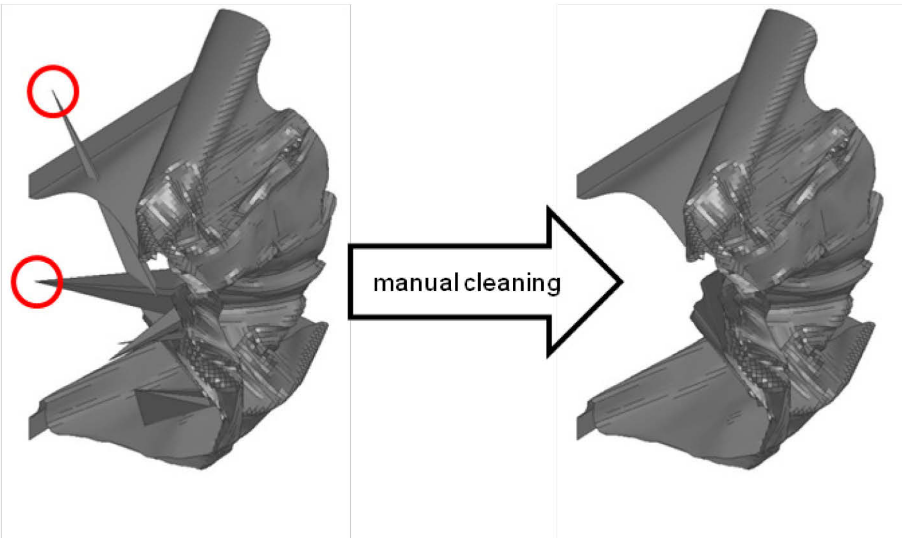


Figure 4.28: Manual cleaning of "deleted" elements.

The material failure also affects the accuracy of the final deformation. Comparable to the treatment of ruptures of the cladding sheet in the physical barrier the deformation of the honeycomb behind the cladding sheet needs to be considered to assess the barrier deformation for the FE model too. Even though, nodal information of coordinates of the deformed and failed cladding plate are available they are not sufficient to represent the exact shape of the hole. Based on the presence of nodal information in the area of the maximum intrusion, all investigated assessment metrics interpolate between these available nodes and the area where the cladding plate fails. Figure 4.29 shows an intruding PEAS (green) into the PDB. The detailed view (right) shows the difference of the shape of the PEAS and the deformed cladding plate due to element elimination.

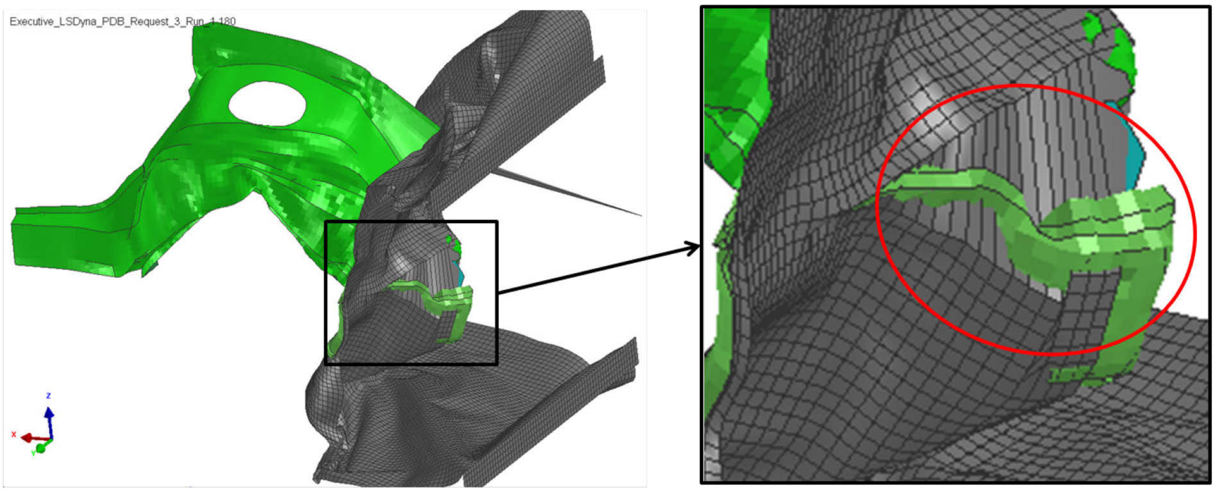


Figure 4.29: Representation of the shape of the intruding PEAS.

The first step to increase the accuracy was to extract the correct shape from the nodal information of the honeycomb elements too. This approach was considered not to lead to the desired results. On the one hand the missing information had to be extracted from a very high number of honeycomb elements which was very time consuming. On the other hand material failure was also observed for the honeycomb parts which lead to the same numerical artefacts as already described for the cladding plate.

Two possibilities were analysed to overcome this problem. The first was the implementation of so called “null shells”. These null shells are shell elements that can cover parts but do not have an influence on the results because no stress/strain calculation is considered. A typical application in numerical simulation is the creation of contact surfaces. However, because the null shells need to be connected to other parts (i.e., the nodes of the cladding plate) they also experience the same deformations. Therefore no additional information was created to better describe the final deformation pattern and reduce the manual post-processing. The second option was an additional plate in front of the cladding plate of the PDB. This additional plate was welded in specific areas to the cladding plate. The basic idea was to create some kind of contact surface with the colliding vehicle which does not have any failure mechanisms and behaves independently from the cladding plate but with the same characteristics. First simulations showed that this approach had the potential to improve the reproduction of the final deformation. Due to the mechanical properties of the additional cladding plate the overall behaviour of the PDB model altered (increased deceleration peak and time shift of maximum deceleration). Because it was not possible to clarify whether or not the altered behaviour is acceptable, this approach was also neglected.

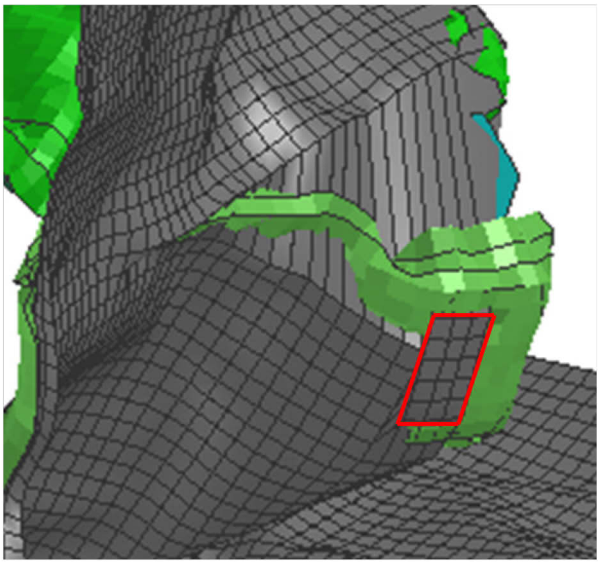


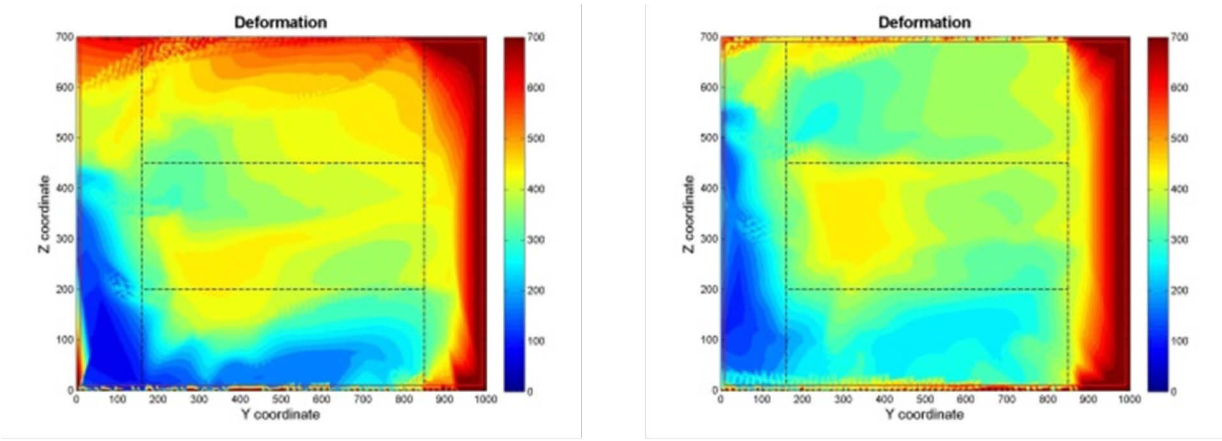
Figure 4.30: Finite elements (red marked) close to the maximum deformation depth for analysis of footprint.

To proceed with the numerical simulation tasks it was decided to accept the inaccuracy resulting from analysing only the cladding plate of the PDB. Figure 4.30 shows a group of nodes of the cladding plate (red marked) very close to the maximum intrusion. Nevertheless, due to the presence of those elements close to the deepest intrusion the assessments of the footprints were possible. Regarding the conducted sensitivity analysis and the simplified vehicle models, this procedure is acceptable. For the development process of a vehicle this method cannot be used. In particular, the prediction of the crash behaviour in frame of the homologation process is crucial, thus this inaccuracy cannot be tolerated. Due to a lack of appropriate post-processing procedures, the extraction of the real footprint from the numerical output remains a time consuming process.

4.4 PDB Sensitivity Analysis – PCM Simulations

The following section summarises the results of the sensitivity analysis of the PDB barrier. As described in Chapter 4.1.2 of FIMCAR Deliverable D2.1 [Lazaro 2013] the main objective of this investigation was, in particular, to analyse modifications of the PEAS and SEAS and the resulting metric assessments. Further parameters were the vehicle mass and the impact velocity. Therefore the parametric design of the PCM model "Executive" should be used to create the planned modifications. Depending on the simulation results, worst case and best case scenarios (combinations of different varied parameters) should be created and the crash performance should be verified in car-to-car simulations. However, it was not possible to finalise this task within the FIMCAR project. Nevertheless the analysis of the deformed PDB will be presented hereafter. All 45 modifications (Chapter 4.1.2 of FIMCAR Deliverable D2.1 [Lazaro 2013]) were rerun against the PDB version 2 FEM model, which had improved overall crash behaviour like rupture of the cladding plate.

A detailed overview of all results containing barrier footprints and assessment metric results can be found in Annex G. First preliminary results indicated that the effect on the footprints of the lower load path was too small. Therefore it was decided to improve the stiffness of the baseline model for all sub frame modifications. Figure 4.31 shows the footprints of the two baseline models.



baseline model – initial sub frame baseline model – improved sub frame

Figure 4.31: Footprints of baseline models with initial design of sub frame (left) and improved design (right).

Even though the sub frame still cannot be detected (initial position in x-direction is 100 mm behind the cross beam), it has a positive influence on the stability of the PEAS. Due to the design of the longitudinals, the whole PEAS tend to bend downwards during the impact against the PDB, see Figure 4.30.

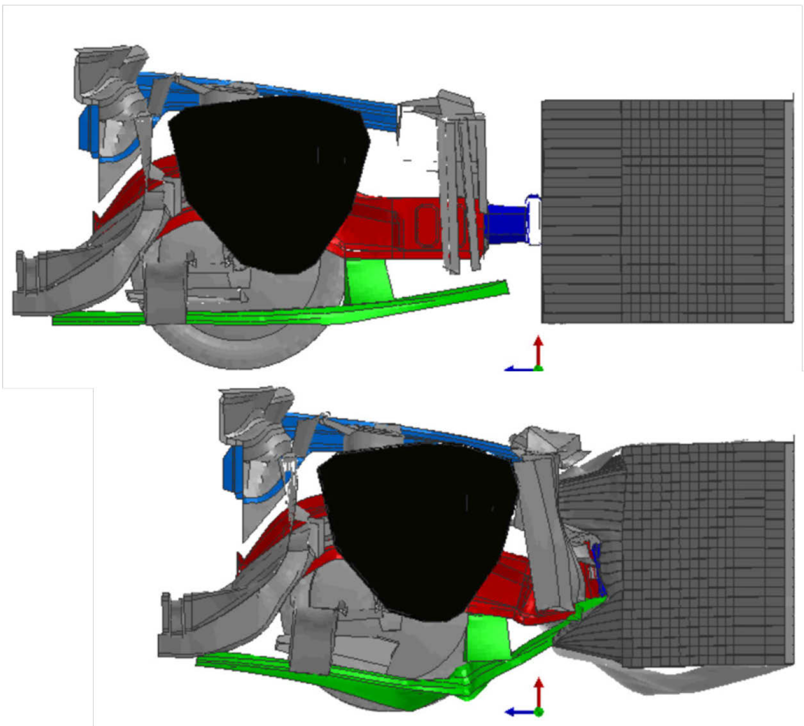


Figure 4.32: Downward bending of the longitudinal (red) during the impact against the PDB.

Due to this effect the resulting footprint of the longitudinal differs from its initial position (see Figure 4.30 upper and lower frame) for most of the Runs 01 to 25.

The following results of the assessment metrics are normalised to corresponding baseline model value of each criterion and are marked with "*". For PPS and Homogeneity value, values > 1.0 indicate increasing scores (better assessment w.r.t the baseline model) and values < 1.0 indicate decreasing scores (worse assessment w.r.t. the baseline model) because high values are intended to correlate well with good compatibility. In comparison high DDY values indicate a poor compatibility, therefore normalised DDY values < 1 indicate an improvement w.r.t. the baseline model. Additionally the computed DDY values are normalised to the preliminary threshold value of 3.5 and are marked with "**".

To understand the assessments of the three compatibility metrics it is important to know that the metrics assess different AoIs. The main difference is the lower horizontal dimension of the DDY assessment area because it takes into account only 60% of the half vehicle width. The distance between the longitudinals of the PCM Executive car is relative large. Therefore the main part of the footprint of the longitudinal is not taken into account. During the development of the DDY it was discussed to use the distance between outer edges of the longitudinals as a reference value for the calculation of the horizontal dimensions of the AoI, if the distance is larger than 60% of the vehicle width. This proposal was not used for the following analysis.

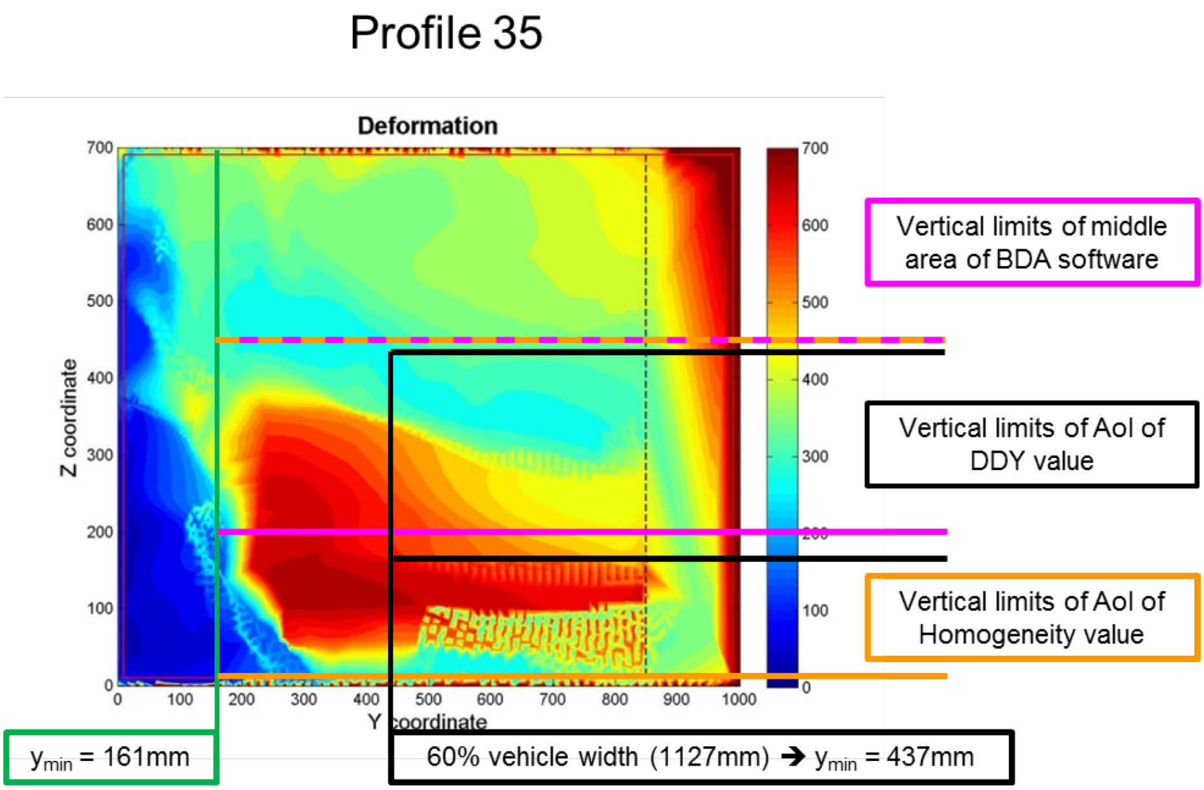


Figure 4.33: Different AoI depending on used assessment metric.

4.4.1 Sensitivity Analysis – Vehicle Mass

As already stated the vehicle mass should have minor effect on the compatibility metrics because otherwise vehicles are discriminated due their mass. Hence this is limited to the intrusion depth which is easier for heavier cars to achieve, the vehicle mass can have an influence on the homogeneity of the deformation pattern. Due to a higher vehicle mass it can happen that the interaction between engine and barrier becomes more relevant, which leads to a more homogenous footprint.

- Parameters:
  decreased mass - engine mass
  increased mass - cowl support and seat cross beam
  Run 01: m_{engine} - 200kg
  Run 02: m_{engine} - 100kg
  Run 03: m_{engine} = 430kg / $m_{vehicle}$ = 1904kg (basis model)
  Run 04: $m_{vehicle}$ + 100kg
  Run 05: $m_{vehicle}$ + 200kg

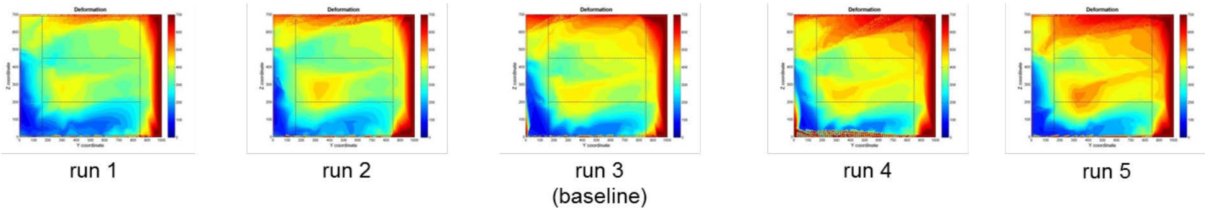


Figure 4.34: Barrier footprints depending on modified vehicle mass.

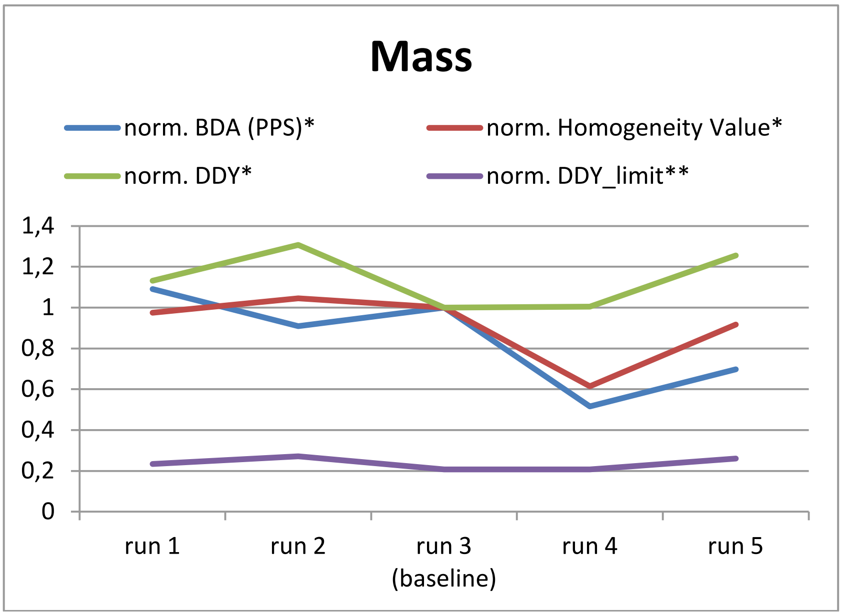


Figure 4.35: Metric assessment depending on modified vehicle mass.

In principle Figure 4.35 shows comparable results. The normalised DDY seems to show less sensitivity to vehicle mass than the BDA and Homogeneity Values. According to the DDY values in relation to the threshold value of 3.5 all vehicles offer a good load spreading. However, the influence of the engine can clearly be seen in Figure 4.34. While the footprints of run 1 and run 2 only show the longitudinal, the effect of the interaction with the engine becomes more relevant (run 4 and run 5).

4.4.2 Sensitivity Analysis – Impact Velocity

Small variations of the impact velocity should have hardly any influence on the metrics. In particular typical tolerances occurring in real crash tests must not lead to large differences in the assessment. To analyse the sensitivity on the vehicle speed the following variations were investigated.

- Parameter: initial velocity
  - Run 06: v = 56km/h
  - Run 07: v = 59km/h
  - Run 08: v = 60km/h (basis model)
  - Run 09: v = 61km/h
  - Run 10: v = 64km/h

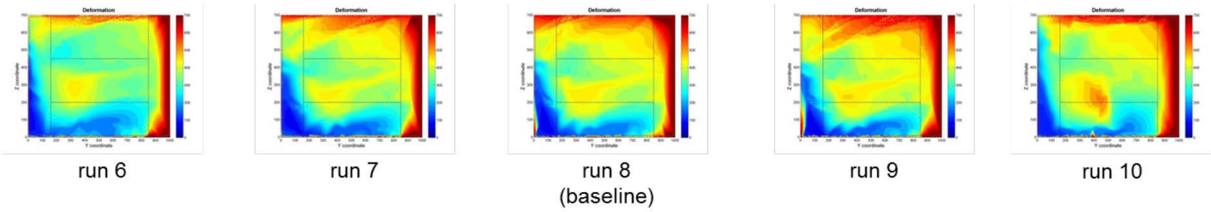


Figure 4.36: Barrier footprints depending on modified impact velocity.

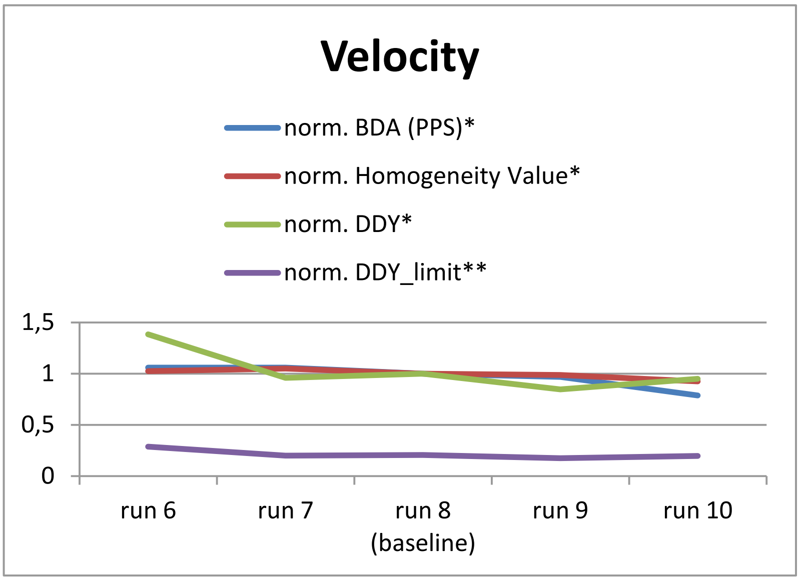


Figure 4.37: Metric assessment depending on modified impact velocity.

As expected the assessment results from all three metrics are virtually identical within ±1km/h (run 7 to run 10). Especially the Homogeneity value and the DDY value seem to be very robust against small variations of velocity.

4.4.3 Sensitivity Analysis – Cross Beam Stiffness

To improve the horizontal load spreading a strong cross beam was proposed to spread the loads e.g. from a centric pole impact to the longitudinals. The objective of the variation of the cross beam stiffness was to analyse if a stronger cross beam can be detected in the footprints and if the metrics are able to address the improved horizontal load spreading.

- Parameter: wall thickness
  - Run 11_w/o cross beam
  - Run 11: t = 0.10mm
  - Run 12: t = 0.90mm
  - Run 13: t = 1.80mm (basis model)
  - Run 14: t = 3.54mm
  - Run 15: t = 10.00mm

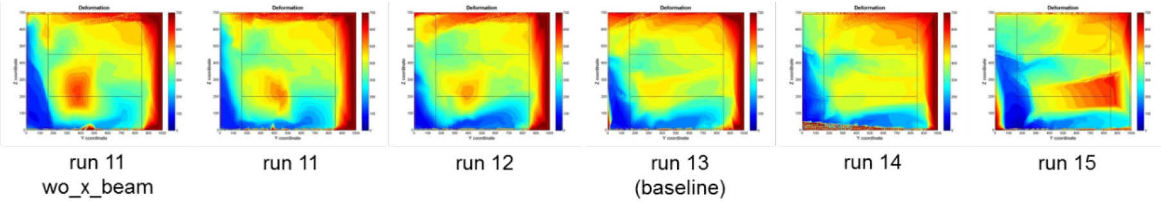


Figure 4.38: Barrier footprints depending on modified cross beam stiffness.

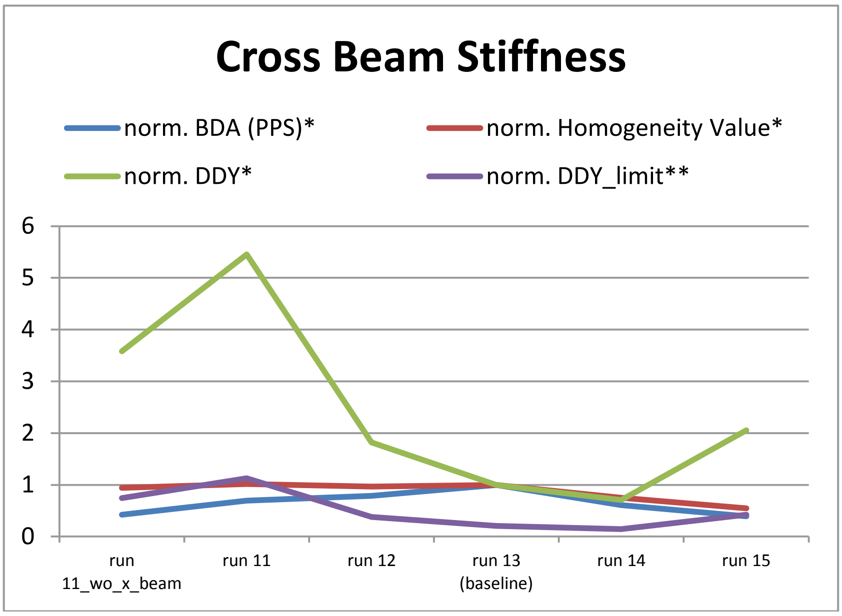


Figure 4.39: Metric assessment depending on modified cross beam stiffness.

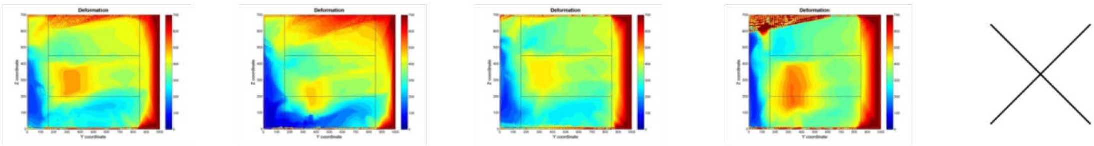
Although the presence of a hole can clearly be seen in Figure 4.38 (Run 11 w/o cross beam and Run 11) only BDA software and DDY detect these holes. The Homogeneity value remains constant for all runs except Run 14 and Run 15. Regarding the horizontal load spreading only DDY value assessed run 14 better than the baseline run which was expected. However all Runs except Run 11 would pass the DDY metric. Run 11 without cross beam passes the metric because the longitudinal bends in outboard direction due to the missing connection between both longitudinals. Thus the longitudinal (and the hole resulting from the longitudinal without crossbeam) is not within the AoI of the DDY metric and was not assessed. As already explained above the issue could likely be solved if the metric considers 60% of the vehicle width or the real distance between longitudinals whatever is larger.

4.4.4 Sensitivity Analysis – Sub Frame x-direction

Several investigations were conducted to analyse the potential of the lower load path in a frontal crash [Park 2009; Stein 2013/1]. All studies indicated a positive trend regarding the forward position of the sub frame for cars that have a suitable connection between sub frame and PEAS (Primary Energy Absorbing Structures). Thus the PDB and the corresponding assessment metrics should be able to detect the presence of a lower load path which is mainly depending on the distance between cross beam and the sub frame.

- Parameter: distance of cross beam and sub frame in x-direction
  - Run 26: very reward ($x_{\text{cross beam}}$ + 500mm)
  - Run 27: reward ($x_{\text{cross beam}}$ + 300mm)
  - Run 28: medium ($x_{\text{cross beam}}$ + 100mm)

– Run 29: forward ($x_{cross\ beam}$)
– Run 30: very forward ($x_{cross\ beam}$ - 100mm) ➔ conflict with bumper



run 26 run 27 run 28 (baseline) run 29 run 30

Figure 4.40: Barrier footprints depending on modified sub frame position in x-direction.

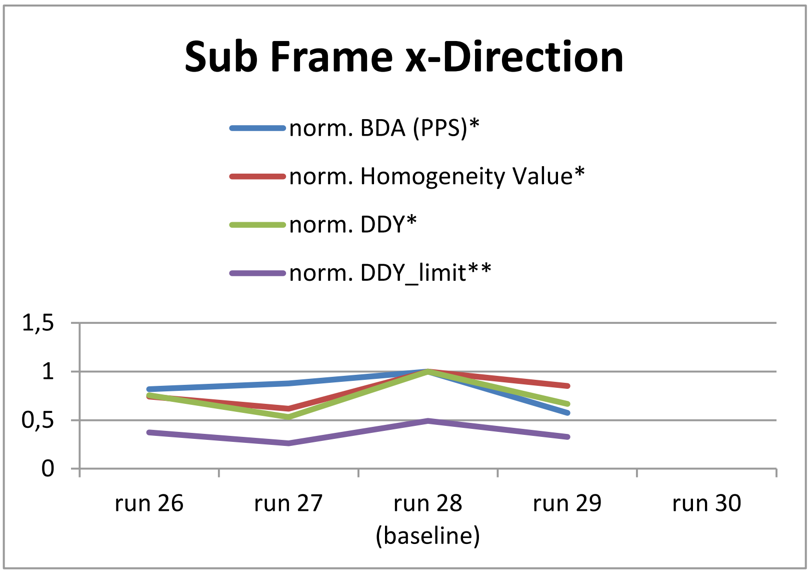


Figure 4.41: Metric assessment depending on modified sub frame position in x-direction.

This example shows contradicting results regarding the assessments. While PPS and Homogeneity value assess all modifications worse compared to the baseline model the normalised DDY value indicate improvements. The subjective assessment of the footprints correlates with the assessment of PPS and Homogeneity value. The main reason is the relative homogenous footprint in the centre of the barrier of the baseline run (Run 28, see Figure 4.40). W.r.t. Run 26 and Run 29 the deformation of the longitudinal is dominating which leads to the expectation of a reduced homogeneity. The main reason for the contradicting rating of the DDY metric is the smaller AoI which did not captured the holes.

4.4.5 Sensitivity Analysis – Sub Frame stiffness

To sustain the crash loads during a frontal impact a specific stiffness of the sub frame is needed. This can be influence either by the geometry of the sub frame or by the material used. In general it was expected that increasing sub frame stiffness should be detected by the metrics and should result in a better assessment than weak sub frames.

- Parameter: wall thickness
  – Run 31: t = 0.10mm
  – Run 32: t = 1.00mm
  – Run 33: t = 2.00mm (basis model)
  – Run 34: t = 4.00mm
  – Run 35: t = 10.00mm

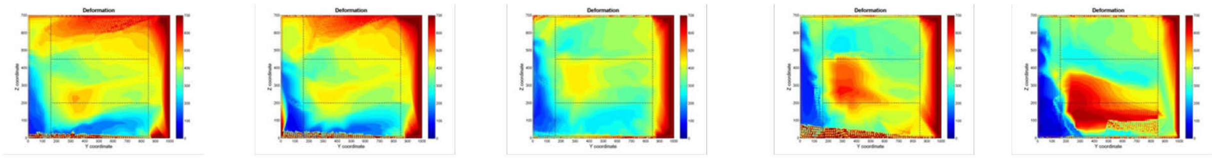


Figure 4.42: Barrier footprints depending on modified sub frame stiffness.

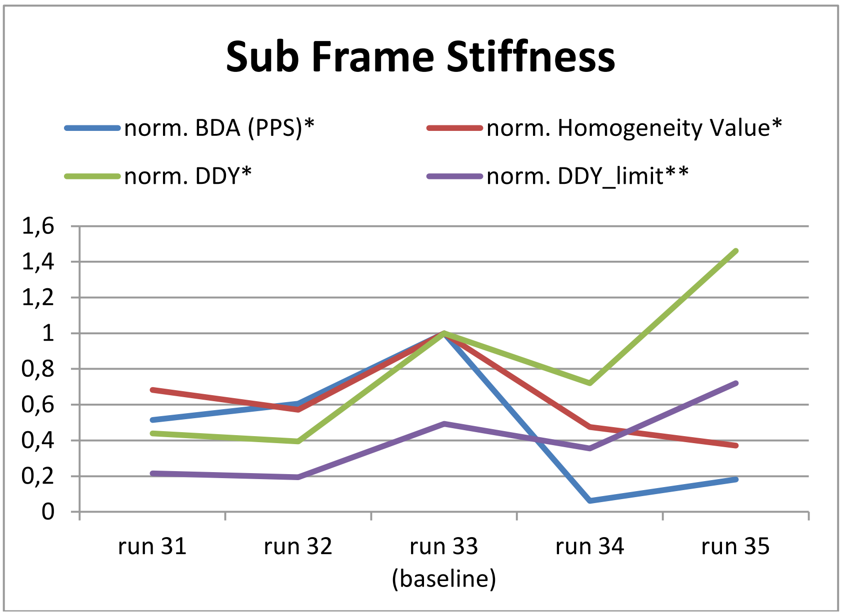


Figure 4.43: Metric assessment depending on modified sub frame stiffness.

The downward bending of the PEAS due to the reduction of the sub frame stiffness (Run 31 and Run 32, see Figure 4.42) was assessed better by PPS and Homogeneity value compared to the baseline model. The DDY value again assessed this as an improvement, because the main affected area is not within the AoI. Regarding the stiffer sub frame runs (Run 34 and Run 35, see Figure 4.42) the rating of the DDY tends be worse but is still below the preliminary threshold value of 3.5. PPS and Homogeneity value assess the stiff sub frame worse too. The reason for the poor assessment of all three metrics is that the stiff sub frame also reinforced the PEAS which lead to a very stiff beam structures resulting in a hole.

4.4.6 Summary PCM Simulations

In total 45 simulations were conducted with variations of 9 different parameters. The main objective was to run a sensitivity study to analyse the effects of structural modification of PEAS and SEAS as well as vehicle mass and impact velocity. The most important findings were shown and explained in detail. The analysis show that the metrics are robust against small variation of the impact velocity which is a finding addressing the R&R requirements. Further results are that the metrics are sensitive to modifications of PEAS and SEAS. However, not in all cases could the same trends be observed. In particular the detection of holes was not possible with all metrics because the AoI of the DDY value was too small to capture the deformations coming from the longitudinals.

The PCM models showed their potential to run a sensitivity study to analyse structural modifications. A large number of different footprints could be created and analysed to investigate the influence of specific changes in design and topology of the crash relevant structures. However the initial design of the models showed that the deformation mode of structures like the longitudinal was not suitable to investigate one specific parameter. Due to the downward bending of the longitudinal the overall crash performance partially showed completely different footprints. Therefore a clear correlation of the modification of one parameter with the metric assessments was not possible in all cases. Future work should focus on an improvement of the PCMs to better address structural changes.

Due to the contradicting results of the metric assessments of all three metric, no clear statement can be made. The results indicate that all metrics need to be revised and maybe modified. The current status does not allow the use of one of them e.g. within the vehicle development process. One possibility to improve the metrics is to further analysis the sensitivity to special effects like improved load spreading or the detection of lower load paths and the appropriate design (in terms of improved car-to-car crash behaviour). Another approach is the elimination of the sensitivity of the metrics on boundary effects as they seem to affect the results if the deformation exceeds the AoI.

4.5 GCM – PDB Simulations

In addition to the simulation results already presented in Chapter 4.1.1 in FIMCAR Deliverable D2.1 [Lazaro 2013] the metric assessments of BDA software, Homogeneity value and DDY metric will be described in the following section. The results focus on the comparison of the three metrics and their potential to assess load spreading within the Area of Interest (AoI) and the detection of holes. Due to the different load path concepts of each GCM category, the detection of the presence of the sub frame is analysed too. The computed values of the three assessment metrics and the corresponding footprints are summarised in Annex H.

The following results of the assessment metrics are normalised to the mean values of each criterion and are marked with "*", see Figure 4.42. For Homogeneity value (TV_upgrade), higher values indicate increasing scores (e.g. > 1.0 means better assessment w.r.t the mean value) and small values indicate decreasing scores (e.g. < 1.0 worse assessment w.r.t. the mean value) because high values are intended to correlate well with good compatibility. In comparison high DDY and TV values (homogeneity assessment by BDA software) indicate a poor compatibility, therefore normalised DDY and TV values < 1.0 indicate an improvement w.r.t. the corresponding mean value. Additionally the computed DDY values are normalised to the preliminary threshold value of 3.5 and are marked with "**".

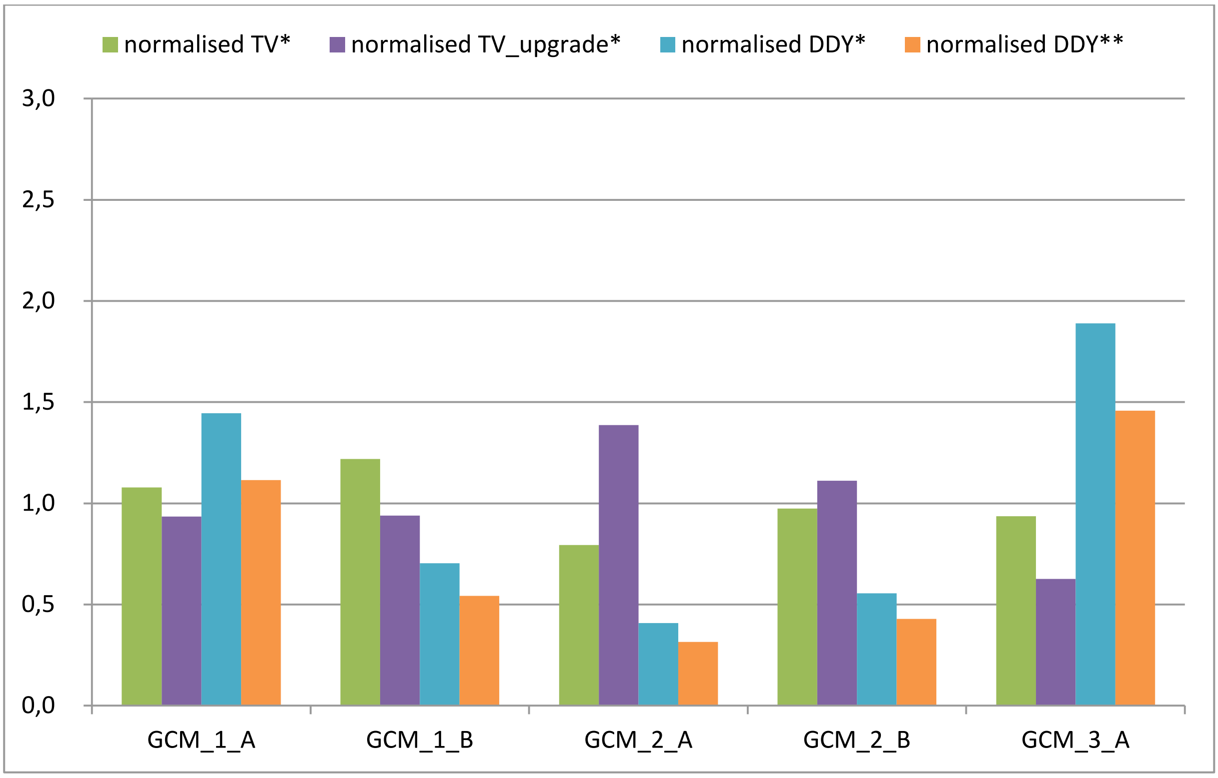


Figure 4.44: Normalised metric assessments of GCM simulations (in relation to mean value; ** in relation to proposed DDY threshold value of 3.5).*

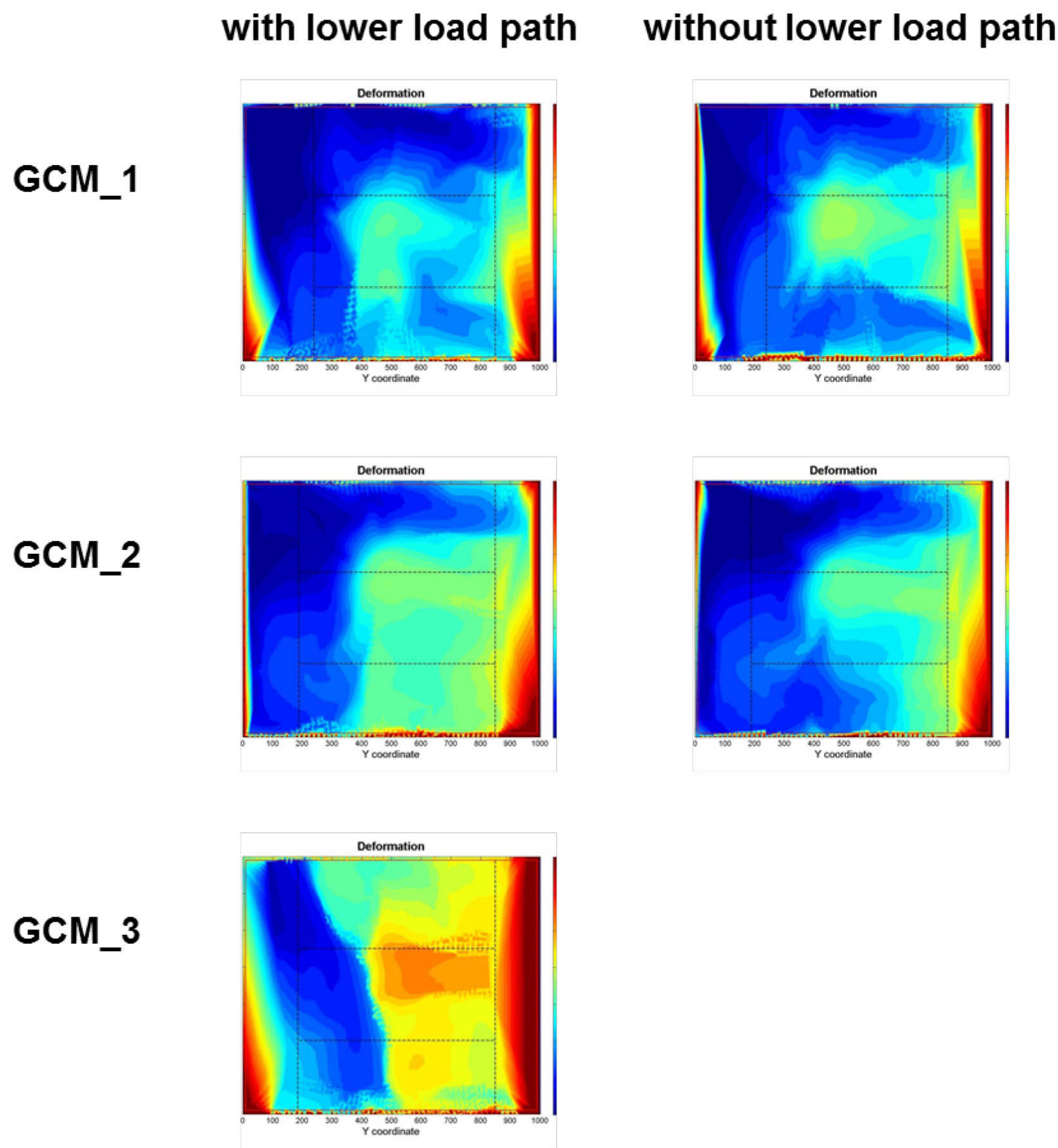


Figure 4.45: Barrier footprints of GCMs.

4.5.1 GCM_1

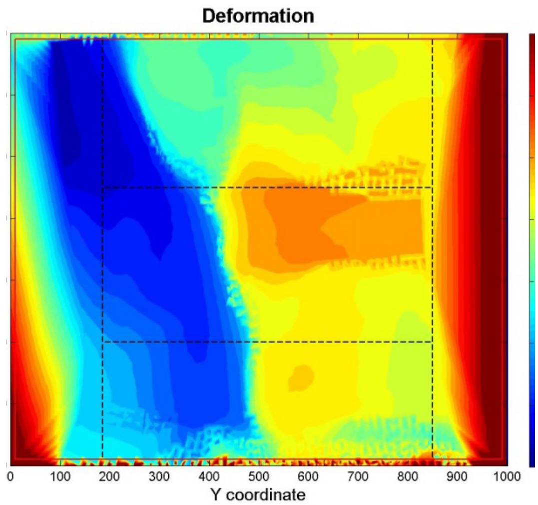
The subjective assessment of the GCM barrier footprints, Figure 4.45, would conclude that the lower load path improves the vertical load spreading and the hole (in the center of the barrier) due to the single load path disappears. The DDY metric clearly distinguish between both deformation patterns. The normalised values of DDY** indicate that the single load path GCM_1 fails the proposed DDY metric, while the same car model equipped with a sub frame passes. The Homogeneity values shows hardly any differences, thus this metric seems not to be capable to detect holes and to distinguish between the directions of the load spreading. The BDA software assesses the sub frame model better too. The main reason for that is the better assessment of the homogeneity (TV value). In total the difference of the PPS scores is higher because additional points are given due to the deeper intrusions in the lower area. That could be an indicator of the ability of the BDA metric to detect lower load paths.

4.5.2 GCM_2

Both footprints show a very homogeneous deformation pattern, see Figure 4.43. Due to the presence of a lower load path the deformed area of the lower area is larger than without the lower path. In particular, the Homogeneity value (TV upgrade) is higher for the sub frame model, however the DDY metric as well as the BDA software (TV value) assess the improved homogeneity too. However, the total assessment of the BDA software shows a contradicting trend. Because the intrusions of GCM_2_B (without lower load path) in the upper area are lower and the intrusions in the lower area are deeper the total PPS is higher for this model, see Annex H. The rating of the intrusion depth is part of the BDA software assessment and described in detail in FIMCAR Deliverable D2.1[Lazaro 2013].

4.5.3 GCM_3

Because there is only one load path concept available for GCM_3 no comparison to an Executive car without a lower load path can be made. Regarding the metrics all values indicate a relative poor assessment. Indeed, the TV value shows comparable results to the other GCM types but due to the deep intrusions the total PPS is worse too. The sensitivity to the intrusion depth was already identified in the analysis of the artificial profiles (Section 4.2.1). Subjectively, the footprint shows a homogenous deformation below the footprint of the cross beam. This indicates that GCM_3 potentially offers enough structures to activate the EAS (Energy Absorbing Structures) of a colliding vehicle. However, the difference between the non-deformed side and the deformed area (see Figure 4.44) seems to have an influence on the metric. W.r.t. the footprints coming from the calculation of Homogeneity value and DDY metric the deformations seem to be relatively smooth, see Figure 4.44.



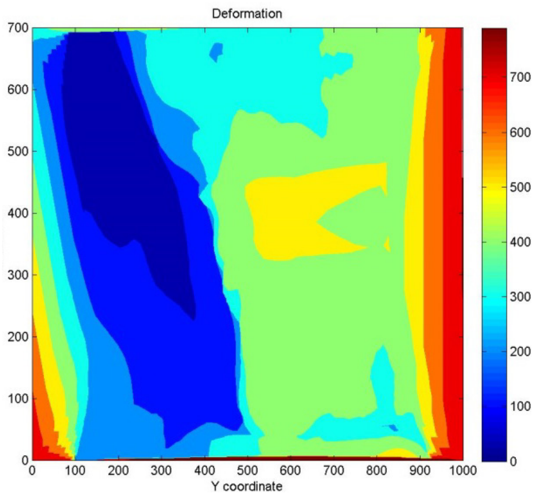


Figure 4.46: Barrier footprint of GCM_3 from BDA software (left) and Homogeneity value and DDY metric (right).

4.5.4 Conclusions GCM Simulations

The GCMs offered the possibility to compare detailed vehicle models with a generic design and different structural concepts. Thus the comparison of the three compatibility metrics regarding an improved load spreading, the presence of holes and the detection of a lower load path was possible. The analysis shows again the dependency on the vehicle mass, because heavier vehicles typically create deeper intrusions than lighter vehicles. However this investigation clearly shows that cars equipped with a lower load path are assessed better than the corresponding model without a sub frame. The additional load path eliminated the presence of holes and improved the homogeneity which could addressed by Homogeneity value and DDY metric

4.6 DDY Value – Updated Assessment Values

In addition to the description of the DDY metric and the overview of the initial vehicle assessments by this metric presented in Section 4.1.2.2, the rating was reviewed in particular to analyse the borderline cases. Figure 4.47, shows the updated DDY values (99%ile, LCW Row 3 and Row 4, 60% of half of the vehicle width) for the test candidates. All analysed test candidates and the corresponding metric assessments as well as the barrier footprints are summarised in Annex I.

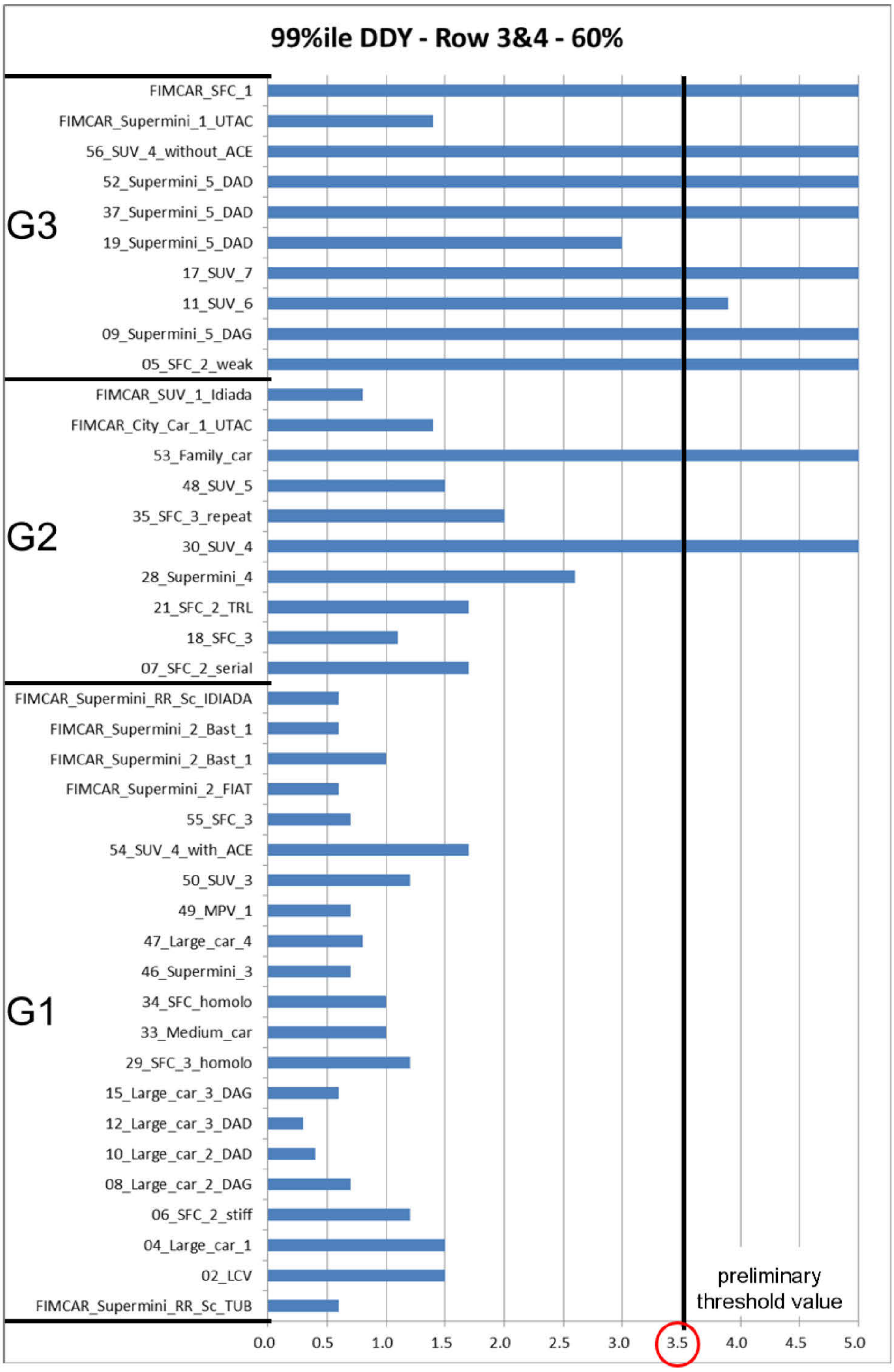


Figure 4.47: Updated summary of 99%ile DDY – Row 3&4 – 60% metric assessment.

4.6.1 Group 1

All reviewed DDY values are a little bit lower than the original assessment in Chapter 4.1.2.2. Therefore the borderline cars of the first comparison are now below the preliminary threshold value. Furthermore the difference between LHD and RHD tested vehicles (e.g. “10_Large_Family_Car_2” and “08_Large_Family_Car_2”) was reduced.

4.6.2 Group 2

Figure 4.46 shows the barrier footprints of the group 2 vehicles. The red highlighted footprints represent the vehicles that still fail the DDY metric. The yellow highlighted footprint shows a deformation pattern with a corrected DDY value, thus the corresponding vehicle passes the metric now.

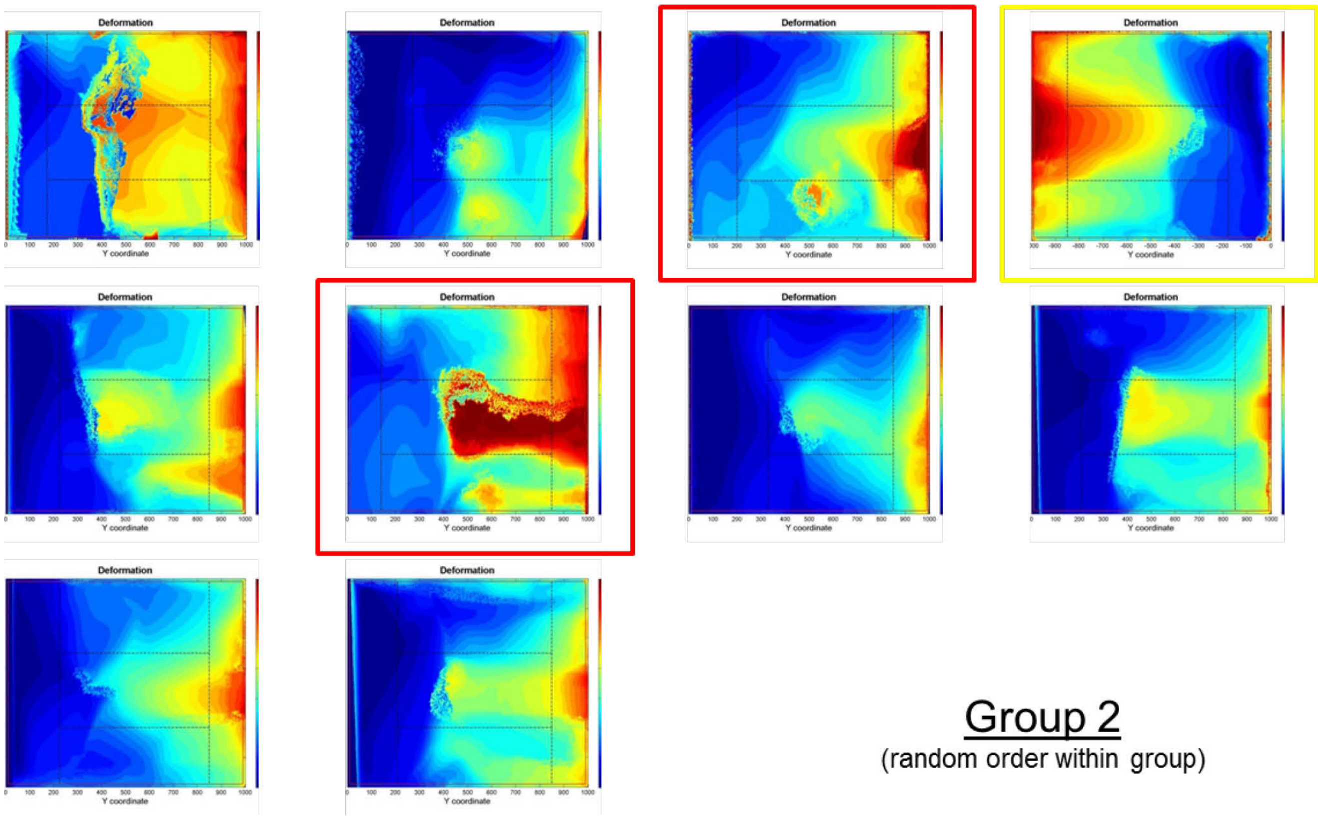


Figure 4.48: Barrier footprints of group 2 vehicles (fail ➔ red flag; pass after review ➔ yellow).

4.6.3 Group 3

Within group 3 there was a change of the pass/failed vehicles too. The yellow highlighted footprints, see Figure 4.47, represents a car that now passes the DDY metric. In comparison with the green highlighted footprint both deformations show the same characteristics which is now addressed by the assessment.

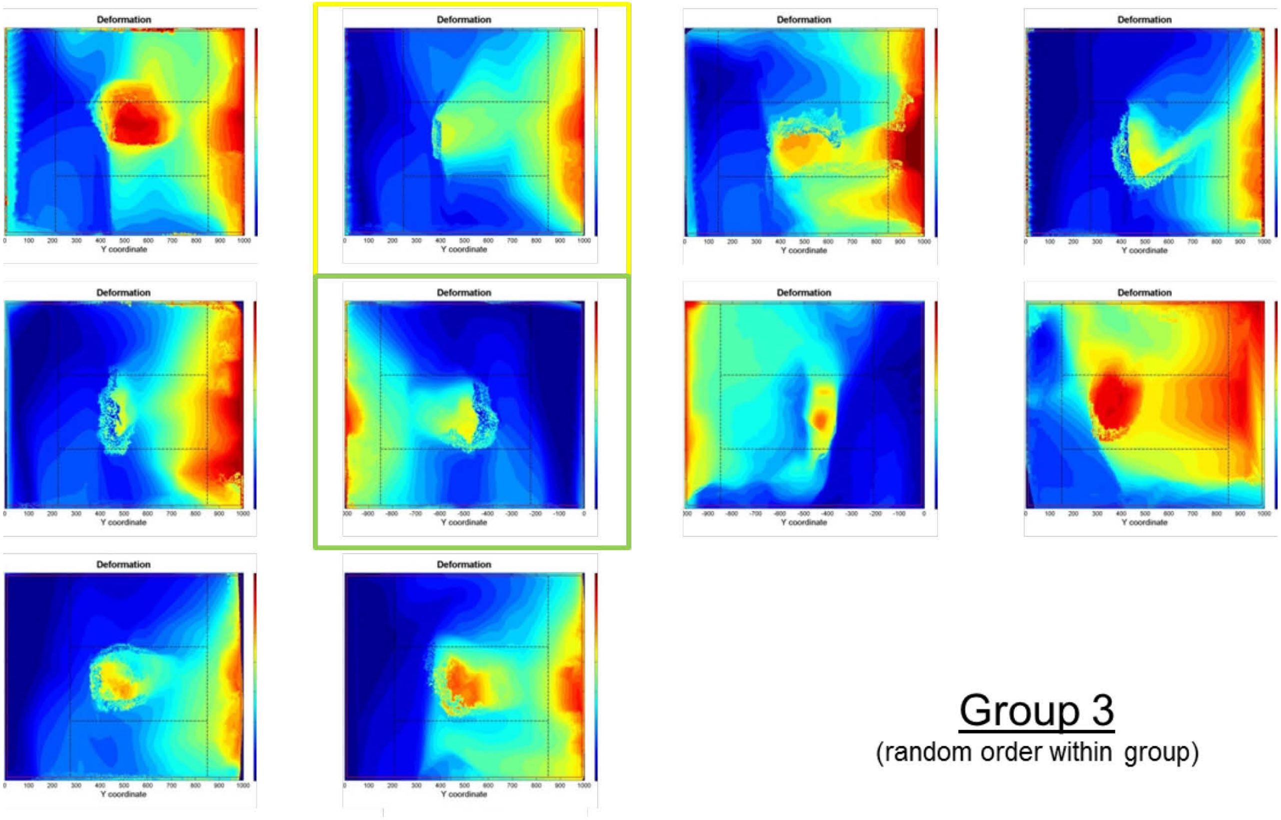


Figure 4.49: Barrier footprints of group 3 vehicles (pass → green flag; pass after review → yellow).

4.7 Comparison of Compatibility Metrics

To compare the three metrics (BDA software, Homogeneity value (TV_upgraded) and DDY metric) the mean value of the each metric was computed and all PDB test candidates and the corresponding assessments were summarised in relation to this mean value and are marked with "*", see Figure 4.48. For PPS (Partner Protection Score) and Homogeneity value (TV_upgrade), higher values indicate increasing scores (e.g. > 1.0 means better assessment w.r.t the mean value) and small values indicate decreasing scores (e.g. < 1.0 worse assessment w.r.t. the mean value) because high values are intended to correlate well with good compatibility. In comparison high DDY values indicate a poor compatibility, therefore normalised DDY values < 1.0 indicate an improvement w.r.t. the corresponding mean value.

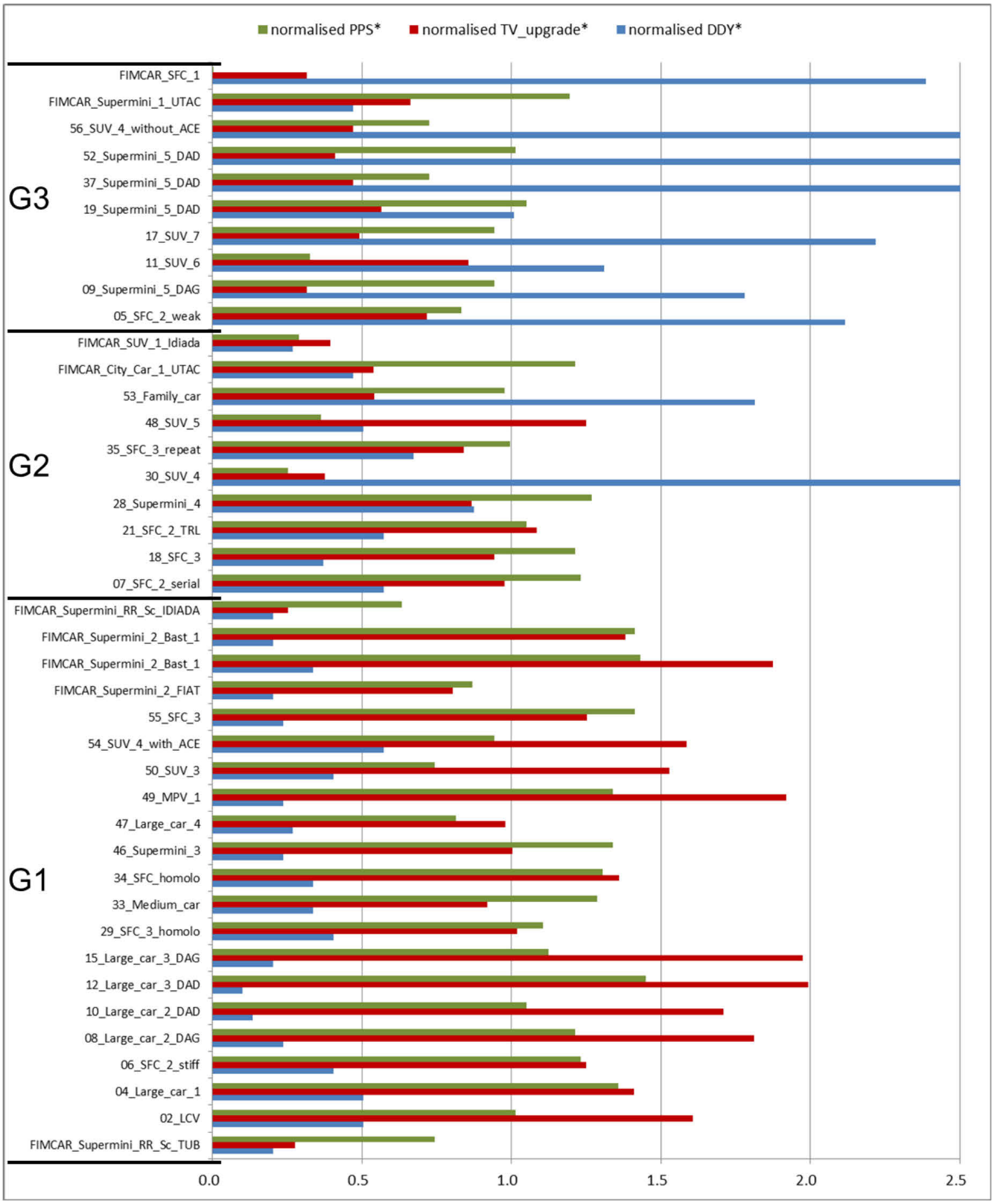


Figure 4.50: Comparison of metric assessments of PDB test candidates.

The DDY and Homogeneity values show the expected contradicting trends, see Figure 4.49. Furthermore, both metrics show a relative large spread. Thus, both metric are capable to clearly distinguish between group 1 and group 3 cars due to their higher, respectively lower normalised values. Indeed, the BDA software shows higher average values for group1 compared to group 3 too, but the difference is relative small, which complicates the definition of appropriate threshold values.

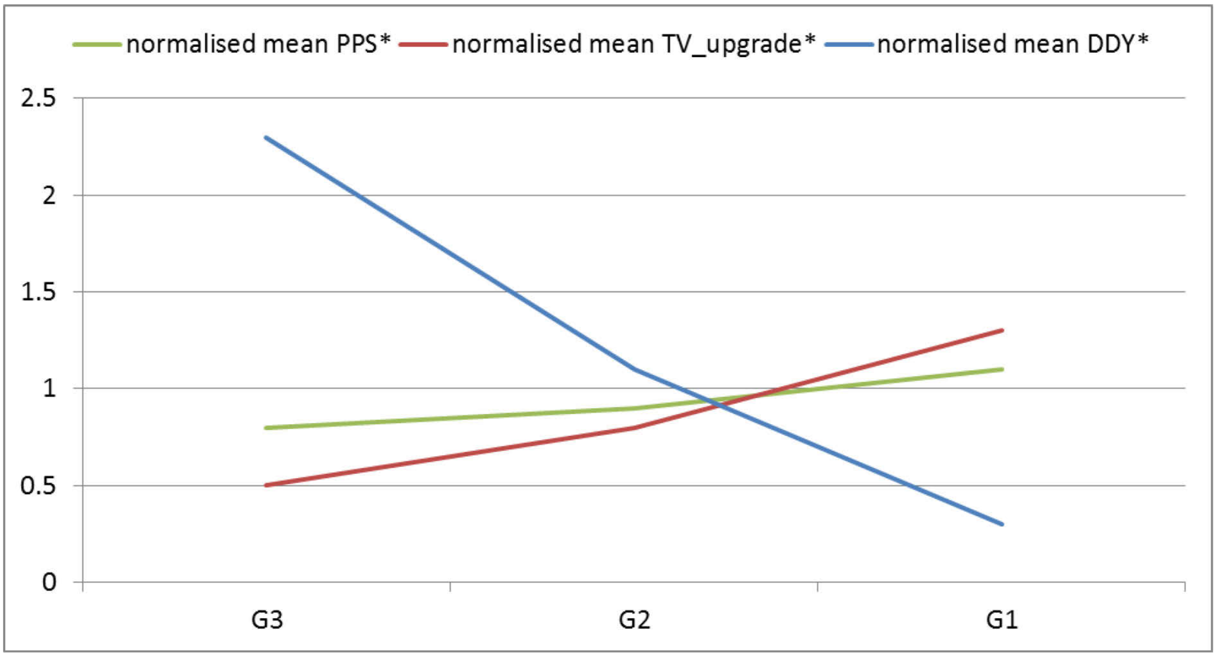


Figure 4.51: Normalised mean values of assessment metrics for group 3 to group 1 cars.

4.8 Definition of Test Severity / Velocity

The proposed test velocity in the PDB test is 60 km/h [Lazaro 2013], the proposed deformable element used in the PDB test aims to harmonise the test severity for different vehicle masses. While with the current deformable barrier used in ODB test (R94 and Euro NCAP) the test severity will increase with the mass of the tested vehicle.

A parameter to assess the severity of a test (or traffic accident) is the EES. In order to ensure the R94 severity an EES of 50 km/h for all type of vehicles will be required.

Details about the definition of the test severity and issues related to the PDB in terms of test severity can be found in Annex B of this deliverable. The main finding was that the PDB produces a more severe test for smaller vehicle, particularly those under 1500 kg than R94. The severity for heavier vehicles becomes less severe. There was not so much data for vehicles above 2000 kg and it was not possible to confirm the PDB would maintain current compartment requirements for all vehicles subject to R94.

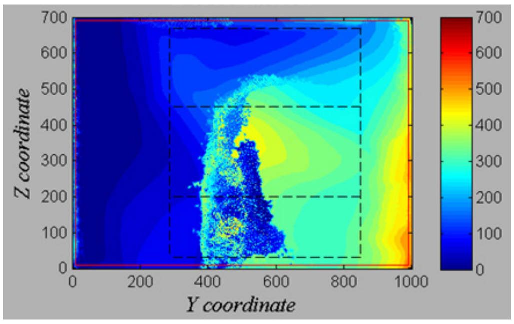
4.9 PDB Barrier Certification

As described in previous sections on this report, the compatibility assessment proposed with the PDB procedure will be based on the post-test, 3D measurements of the deformable barrier. Therefore, it is essential to define the deformable element and the post-test 3D measurements method. Both items are described in the annexure of this report.

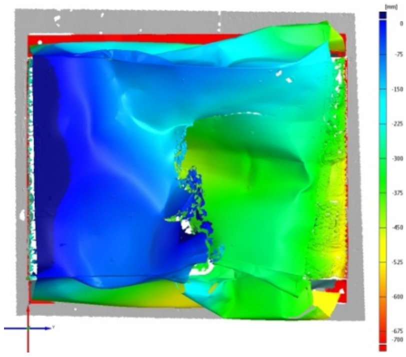
A key factor of the PDB test procedure will be the new proposed deformable element. The definition of this deformable element can be found in Annex 3 of this report. The proposed barrier will require a certification process to validate the behaviour of the deformable element. The certification of the deformable element will consist of a dynamic test to be performed by the barrier manufacturer.

4.10 Development of PDB Scan Procedure

The PDB scan can be performed with different technologies and the different methods have been investigated in WP2. Annex D of this deliverable describes the method proposed by UTAC, a faro arm with laser scanner.



UTAC scan method



IDIADA scan method

Figure 4.52: PDB scan methods.

Alternative methods can be used to conduct the PDB scan, Figure 4.52 shows the Supermini 2 barrier tested at FIAT scanned using two different methods, UTAC and IDIADA. Comparable results on PDB criteria were found using both methods. The analysis of differences in the scanning is described in the R&R section (Chapter 5.2).

During the FIMCAR's investigations, the PDB criteria has been calculated using a reference mesh with 1 mm resolution which is then averaged over 5 mm calculation zones. Therefore, PDB scan methods should provide a mesh size of at least 1 mm.

In the following section additional information to the scan procedure, see Annex D, will be given. The presented information is mainly the result of an interview with consulting engineers which were in charge with one of the repeatability scan of a PDB barrier.

4.10.1 Limitation of Scanning Process

One of the main questions regarding the R&R issues was, if the scanning process depends on the person, which is responsible for scanning the barrier. According to the consulting engineers the quality of the scanning method described in Annex D, does not depend on the user. User specific scanning (e.g. multiple scanning of the same area, horizontal or vertical movement of the scanner) will not affect the results. However, w.r.t. the presence of holes or covered pockets, the digitisation of theses geometries depends on the ability of the user in handling the scanner. Another important factor is the used contactless scanner system. Three relevant systems are listed below:

- structured light scanning
- manual 3D laser scanning (as described in Annex D)
- remote control profile scanning

Regarding footprints of PDB with deep or covered holes, the three systems offer different potentials to capture all necessary information to assess the deformation correctly.

4.10.2 Sensitivity of Scanning Process

Due to the fact that there is no commonly agreed procedure to scan 3D objects like the PDB there is also no information available how the scanning procedure can influence the digitisation of the deformed PDB and how the quality of a scan can be assessed. According to the consulting engineers, the quality of the scan can be ensured and compared by the following values:

- Calibration of scanner
    - Should be done before each scanning (or according to the agreement)
- Standard deviation
    - Automatically computed by the scanner system after the scanning process

Regarding to the standard deviation no thresholds are available distinguish between good or poor scans.

Potentially the 3D scanner systems offer different setups which can have an influence on the result. Most important settings are accuracy and resolution. Accuracy is the ability of the scanner system to sample the surface of an object and to measure surface irregularities. Resolution describes the level of detail of the output. A high-definition output contains more detailed information of the scanned object then a low definition output. While the accuracy of the scanner depends on the used system the user can choose between different setting to create the output and the corresponding resolution. Basically the user can define to take the highest resolution in all areas of the scanned surface. This method results in very large output files (STL files need to be in ASCII format to be workable by the PDB assessment tools) which are difficult to handle in post-processing and cause time consuming calculations. To avoid these disadvantages the scanner systems offer special user routines which automatically reduce the number of scanned points in smooth areas and adjust the number of necessary points in areas where a higher resolution is needed to capture the geometry. How these routines work and how they affect the digitisation process could not be clarified. In general a rule of thumb is used to scan 3D objects which is very familiar to signal processing applications: “the sampling rate of scanning should be 10 times higher than the needed resolution”. According to the experiences of the consulting engineers, the objects which were scanned w.r.t. this rule of thumb should provide R&R conform requirements.

In general the efficiency of the scanning process can be improved if the surface will be matted with special matting sprays, see Figure 4.53 . In that way reflections of the laser and low contrasts which interfere with the measurements can be avoided. As described in Annex D, matting of the surfaces is strongly recommended.

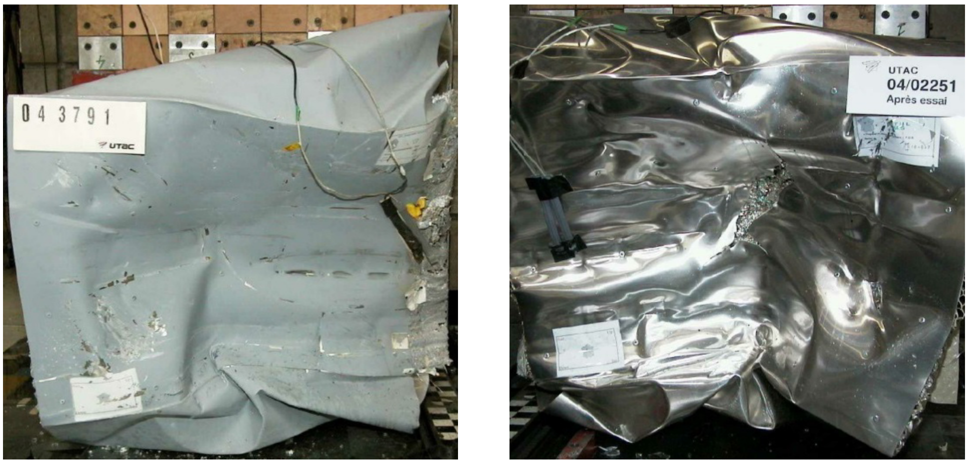


Figure 4.53: Mat surface (left) and bright surface (right) of PDB cladding plates.

4.10.3 Manipulation of Data

To avoid unintended manipulation of the data, possibilities to check the originality where discussed. Basically an STL file contains information about the position and the orientation of a vertex and the connection to a neighboured vertex. This information can be manipulated easily with typical pre-processors used for FEA or CAD applications. Simple checks like date of creation or modification enable the user to control the data. However as simple as the check of this as simple is the manipulation of those data. A further possibility is the cyclic redundancy check (CRC) to verify that there is no loss of data while digital transferring or saving the file. A high level of security guarantees a digital signature, but this feature is not provided by the STL format.

4.10.4 Improvement of PDB for Definition of Origin of Coordinate System

The localisation of the origin of the reference coordinate system is described in Appendix D. Due to deformations on the lower honeycomb edge of the non-impacted side of the PDB the positioning of the reference frame is relative inexact. In particular the localisation of the origin is part of the post-processing after the scanning. Depending on the accuracy of the scan it is nearly impossible for the user to define local axis on the barrier which are parallel to the global coordinate system. The results are small deviations especially regarding the measurement of intrusions into the PDB which can have an influence on the assessment metrics. To simplify the definition of the local coordinate system and therefore to improve the computations of the assessment metric it is proposed to add a rigid cube to the corner of the PDB, as shown in Figure 4.55 where the origin of the local coordinate system should be placed.

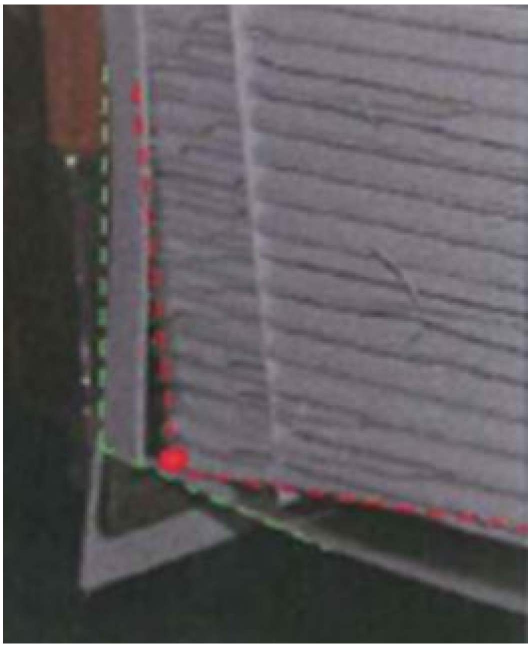


Figure 4.54: Localisation of origin of local coordinate system as described in Annex D.

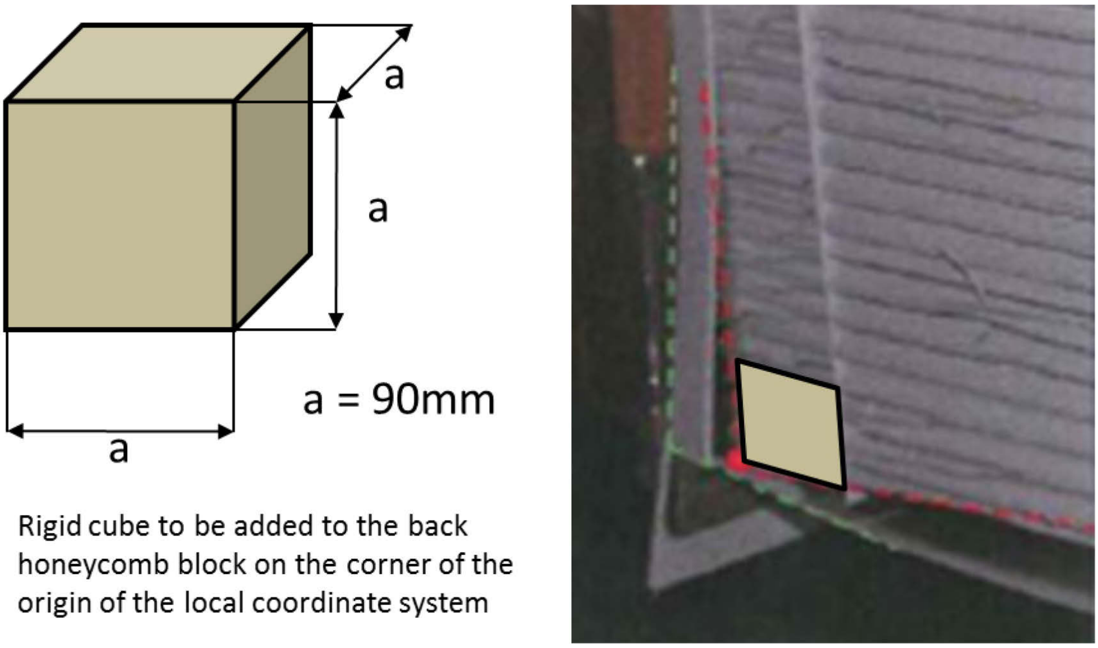


Figure 4.55: Proposal to improve the PDB with a rigid block to simplify the localisation of the local coordinate system.

As described in, the rigid cube can be added to the back honeycomb block of the PDB on the non-impacted side. The outer edges of the cube should be measurable by the scanner. Thus the user can clearly define the local coordinate system within the post-processing. This feature should improve the handling and the preparation of the STL files and should improve the scanning process to become more independent from the user.

4.10.5 Treatment of Folds – Ray Tracing

In some cases the footprint of the PDB showed a deformation pattern where some areas are covered by the cladding plate. This can be a result of failure mechanisms due to rupture of the cladding plate, or the vehicle rotates and pushed a pocket into the honeycombs or while removing a vehicle or components of a vehicle which stuck into the barrier. Figure 4.56 shows two examples.

Figure 4.56: Covered pocket due to rotation of the vehicle (left) and covered areas due to rupture of the cladding plate (right).

As already described these footprints can cause problems depending on the ability of the user to scan the whole surface but one of the main issues is the presence of multiple layers of the barrier (frontal view) due to folds. Figure 4.57 shows the corresponding interpretation of the PDB scans analysed with BDA software v1.0.

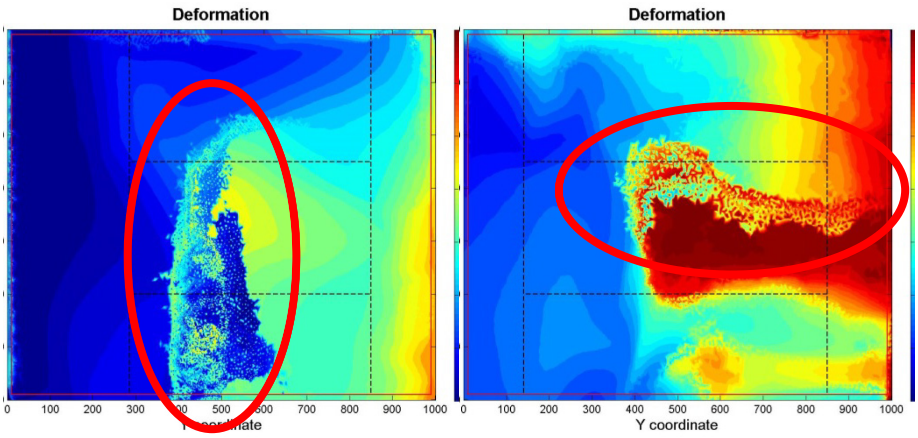


Figure 4.57: Interpretation of scans by BDA software v1.0 of covered pocket (right) and rupture of cladding plate (left).

The red circles in Figure 4.57show that during the scanning process the foremost layer was scanned too which causes interferences in the interpretation of the footprint and therefore influences the assessment by BDA software. The critical parameter is the calculation of the homogeneity of the deformed area which basically is analysed by the total variation of the gradient of the deformation of neighboured points. Folds as well as the geometry of honeycombs (if the cladding plate does not cover the honeycombs the laser goes into the honeycomb due to their orientation and the bottom of the corresponding PDB layer is measured) can cause “noise” within the area of interest and thus can make a correct assessment not possible.

To handle this problem two methods were developed and implemented into the Matlab scripts developed by VTI and TNO, see Chapter 4.1. The most promising approach to reduce interfering areas and to assess the real deformation depth was the ray tracing approach.

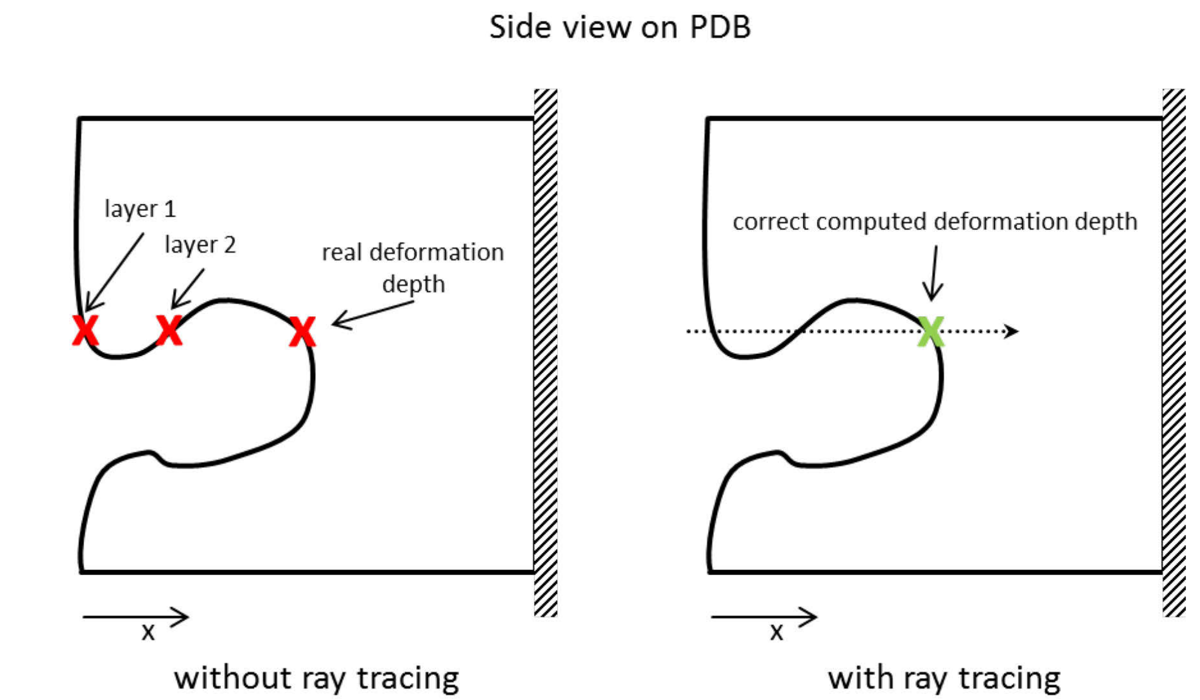


Figure 4.56: Principle of ray tracing.

Figure 4.56 shows basic idea of ray tracing. Mathematically a ray parallel to the x-axis detects multiple layers and only takes the highest x value (= deepest intrusion) into account. The following calculation steps, e.g. for homogeneity value or DDY metric, are based on the maximum x values. Thus no interferences influence the assessments negatively. Exemplarily Figure 4.57 shows the same PDB scans computed with ray tracing as already described in Figure 4.55.

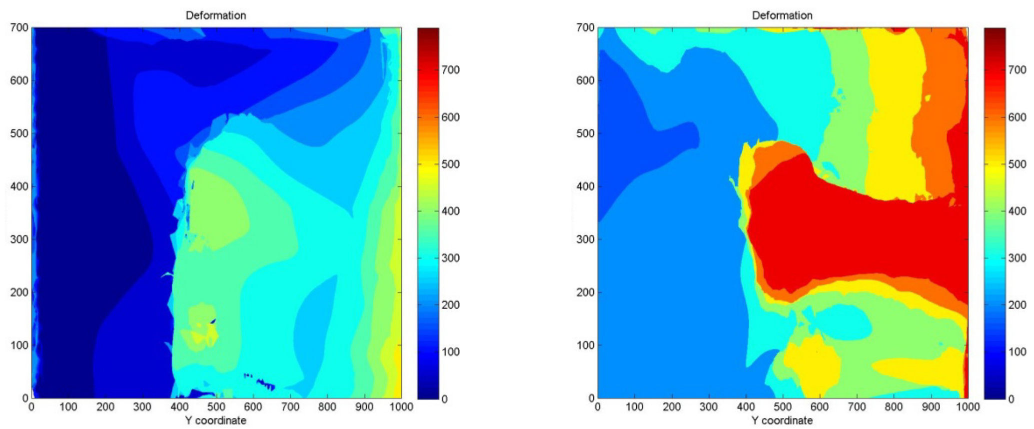


Figure 4.57: interpretation of scans analysed with ray tracing, covered pocket (left) and rupture of cladding plate (right) in comparison to the interpretation without ray tracing shown in Figure 4.55.

The ray tracing offers the possibility to scan the PDB after the crash and excludes multiple layers due to this kind of post-processing. Automatically the real deformation depth is computed by the ray tracing approach and ensures repeatable results. Another method is a user controlled scan, where covered areas are manually uncovered to scan the maximum intrusion into the barrier. But this method is very sensitive to the experience and the ability of the user and can cause belated deformations or rupture of the barrier. The manual post-processing after the scanning is the third possibility to remove folds or areas which can influence the assessment. This manual preparation of the data is very time consuming because there are no automatic algorithms known to delete multiple layers with FEA or CAD tools. Furthermore a manipulation of the STL data cannot be checked if this method is used.

5 VALIDATION OF PDB PROTOCOL

5.1 Validation of Concept

The validation of the PDB procedure involved different analyses of PDB tests performed in FIMCAR and the associated car-to-car test series. The aim of these studies was to show that a vehicle which exhibits underride and other “compatibility” problems in car-to-car tests will FAIL the metric and those which do not show any issue will be assessed appropriately by the PDB test metric and performance limits.

Clear examples of vehicles that should PASS the metric as result of the car-to-car tests are the Supermini 1 and Supermini 2. The Supermini 2 exhibits a “compatible” situation in the aligned and misaligned crash tests, while Supermini 1 showed a “compatible” situation in the aligned conditions (both cases OK the load spreading). Both vehicles were tested in WP2 and passed the structural alignment metric requirements.

The SUV 1 vs SFC 1 car-to-car tests have shown “compatible” situations, i.e. acceptable self-protection in tested cars as well as an equivalent passenger compartments for both vehicles. Those results apply for both, aligned and misaligned tests. On the other hand, the SUV 2 vs SFC 1 showed an “incompatible” situation, in this test the SFC 1 was locally deformed in the footwell area producing higher intrusions in the area and high inward pedal displacements.

From the PDB deformation, we can conclude that the SFC 1 will fail the metric. This result is in line with the SFC 1 vs. SUV 2 car-to-car test.

5.2 Repeatability and Reproducibility

5.2.1 Analysis of FIMCAR R&R Data

In order to investigate the R&R of the PDB, the FIMCAR consortium decided to take the Supermini 2 as a vehicle to be tested and analysed. As agreed by the FIMCAR consortium the R&R analysis includes three tests of an identical vehicle in two different FIMCAR laboratories.The tests were performed in two different laboratories, FIAT and BASt. The same Supermini 2 model, engine and vehicle option was used in all case, see Table 3.

Table 3: Supermini 2 Test matrix.

Vehicle to test	Laboratory	Test Date	Test configuration	Objective	Partner-protection
Supermini 2	FIAT	Jun 2011	PDB60	Test severity validation (self-protection) and comparison with other test modes (FWRB and MPDB)	Good performance expected
Supermini 2	BASt	Jan 2012	PDB60	Repeatability issues	Good performance expected
Supermini 2	BASt	Apr 2012	PDB60	Repeatability issues	Good performance expected

5.2.1.1 Description of the Supermini 2 Front Structure

The Supermini 2 is a super mini car equipped with two energy absorption structures (PEAS & SEAS) and an upper structure that includes a front-end connected to the radiator support at the bonnet leading edge area.

Figure 5.1: Supermini 2 front structure.

As shown in Figure 5.1 the centreline of the PEAS (in red) are positioned 565 mm above ground level which is inside the interaction area defined in FIMCAR (Rows 3&4, 330 to 580 mm). The SEAS lie between 300 to 350 mm above ground, therefore, partially interacting with the common interaction zone defined in FIMCAR. Both structures are longitudinally extended forward to the front-end of the car and incorporate steel cross beams, which are considered part of the front structure.

For the above mentioned front structure characteristics the Supermini 2 is considered a good candidate for compatibility. This assumption was checked and confirmed in FIMCAR. A set of car-to-car tests was performed in order to study the Supermini 2 performance in this kind of crash. Results of the Supermini 2 car-to-car tests can be found in FIMCAR Deliverable D6.1 [Sandqvist 2013].

Table 4: Supermini 2 R&R Test set-up.

Crash Lab.	Car model	Test #	Test mass [kg]	Velocity [km/h]	Ride height measurements		Impact point	
					Front [mm]	Rear [mm]	Horizontal [mm]	Vertical [mm]
FIAT	Super-mini 2	17292	1165	60.24	L 613 R 615	L 623 R 622	0	Up 10
BASt	Super-mini 2	FM02 OPDB	1165	60.01	L 622 R 619	L 614 R 615	Left 35	Up 12
BASt	Super-mini 2	FM03 OPDB	1164	60.08	L 634 R 633	L 618 R 620	Left 87	Low 7

The overlap of the two tests performed at BASt was above the tolerances (20 mm), however, no significant influence was identified on vehicle pulse, dummy reading and vehicle intrusions by the larger overlap. A significant effect on barrier deformation and further metric investigations is expected, however. In particular, for the BASt test no.2 (87 mm horizontal deviation to the left, overlap over 50%).

The pictures below show the Supermini 2 cars before and after tests performed at FIAT and BASt laboratories.

FIAT test BASt test no.1 BASt test no.2

Figure 5.2: Supermini 2 pre-test.

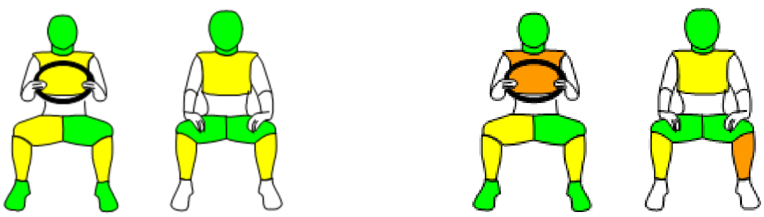
FIAT test BASt test no.1 BASt test no.2

Figure 5.3: Supermini 2 post-test.

In addition to the dummy results and vehilce intrusions, the PDB barrier of the three tests has been scanned and analyed. The objective is to investigate the R&R of the proposed compatibility metrics.

The non-firing of the safety restraint system of BASt test no.1 (FM02OPDB) makes the dummy results unrealistic and non-compareble with the other two Supermini 2 tests. Therefore, we can only compare the test performed at FIAT and the second test performed in BASt (FM03OPDB).

FIAT test BASt test no.2



Driver: 12.658 Driver: 11.932

Passenger: 14.246 Passenger: 13.487

Figure 5.4: Supermini 2 dummy readings.

Comparable results were obtained in terms of dummy values, Figure 5.4. As well as in terms of vehicle pulse and vehicle intrusions, Figures 4.15 and 4.16, respectivelly.

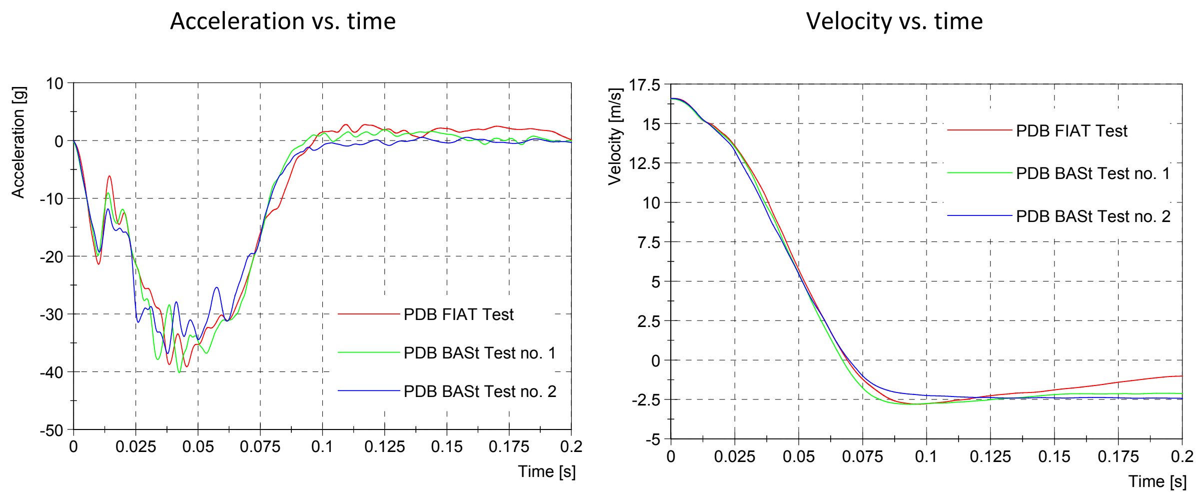


Figure 5.5: Supermini 2 Test pulse.

Minor A-Pillar intrusions were measured in all three tests, minor intrusions at the footrest area were recorded in all cases below 50 mm.

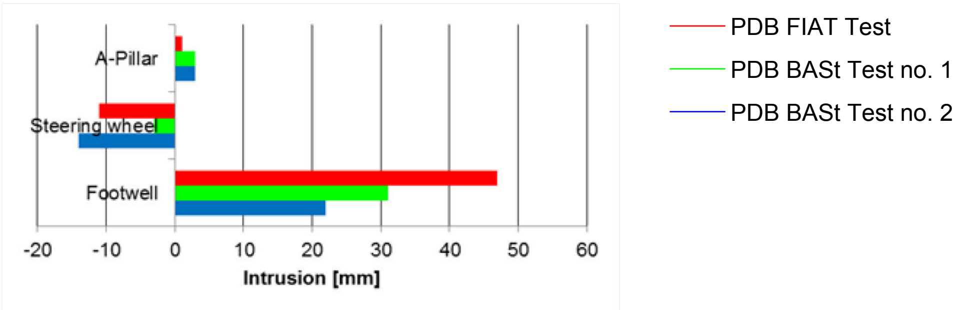
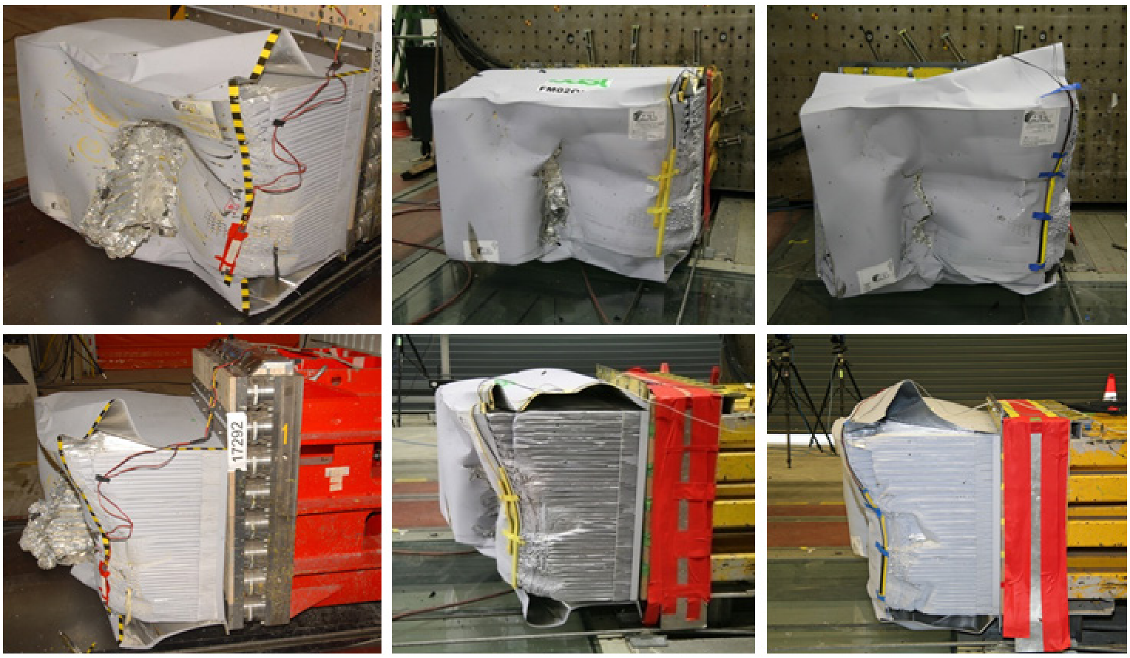


Figure 5.6: Supermini 2 intrusions.



FIAT test BASt test no.1 BASt test no.2

Figure 5.7: Supermini 2 PDB deformation.

In all the three cases, the lower load path has well deformed the barrier. The large vehicle overlap of BASt test no.2 can be observed in the barrier deformation.
Figure 5.8 gives an overview of the three R&R barrier footprints. It has to be noted that “Test 2 @ BASt” had a horizontal impact accuracy greater than the specified tolerance (horizontal overlap with PDB was higher than 50%) whereby the metrics were influenced. The subjective analysis of the footprints, see Figure 5.9, shows comparable deformation patterns. In particular, the repeatability tests (Test 1 and Test 2) show almost identical scans, disregarding the difference due to the wrong horizontal overlap.

Table 5 summarises the ratings of the three metrics. PPS and Homogeneity value assess "Test 3 @ Lab 2" worse compared to the other two tests. The high assessment by the BDA software for Test 1 is a result of additional assessment credits in the homogeneity rating, which is not the case in the other two tests. Furthermore, Homogeneity value and DDY metric are influenced by the larger horizontal overlap with the PDB, but the Homogeneity value indicates an improved compatibility while DDY indicates deterioration. However, the coefficient of variation shows relative high numbers for the deviation from the mean value for all three tests which indicates the importance of impact accuracy.

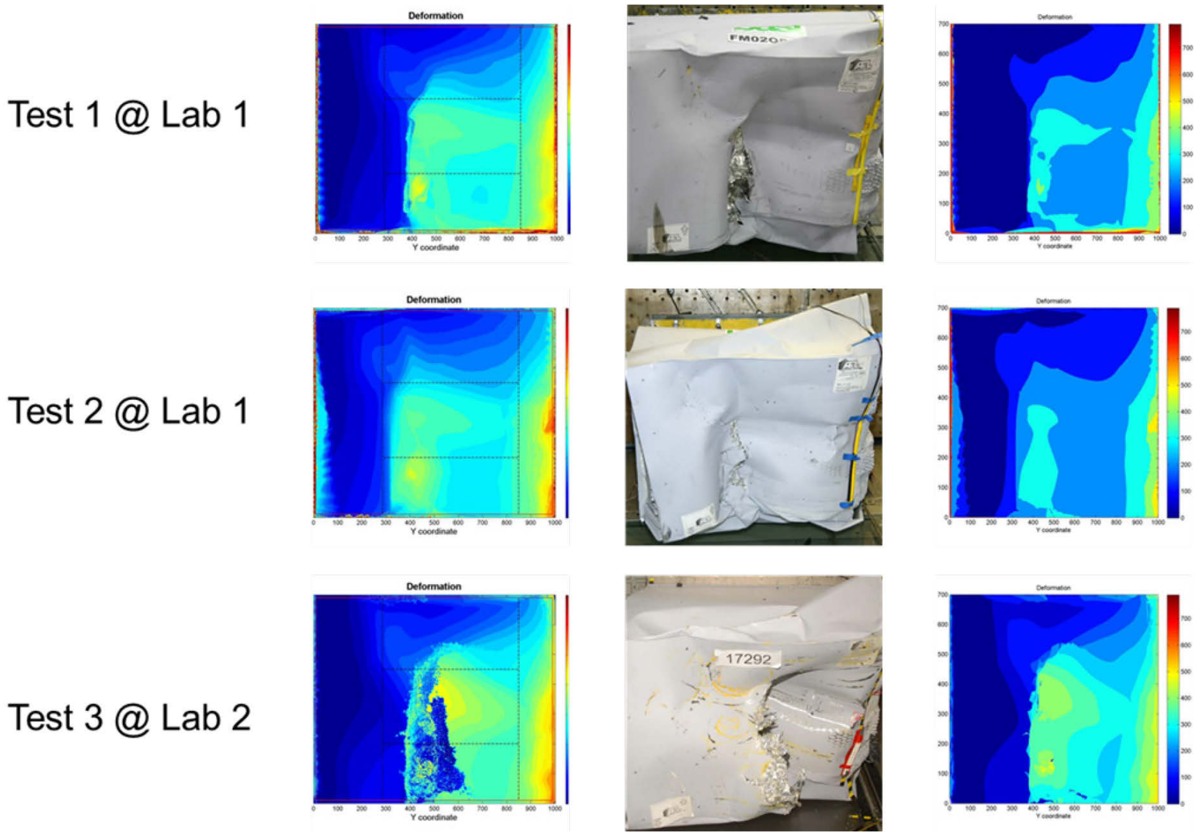
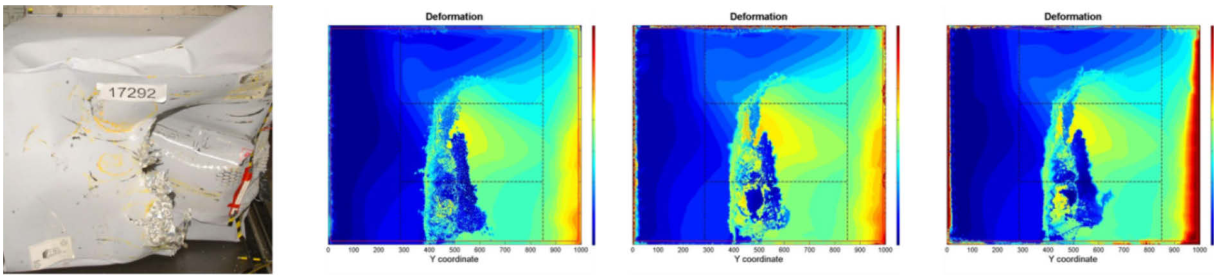


Figure 5.8:FIMCAR Supermini 2 PDB tests.

Table 5: Comparison of metric assessments of FIMCAR Supermini 2 PDB tests.

	PPS	Homogeneity value	DDY
Test 1 @ Lab 1	7.8	209,418,168	0.6
Test 2 @ Lab 1	5.6	284,247,959	1.0
Test 3 @ Lab 2	4.8	122,006,265	0.6
Mean value	6.1	205,224,131	0.7
Coefficient of Variation	25.6	39.6	31.5

Figure 5.9 shows the barrier footprints of the same PDB barrier scanned by different labs. Subjectively all three scans show identical results. The challenge of scanning this barrier was that parts of the deformation where covered by folds. As described in Section 4.10.1, the scanning of covered area depends on the experience of the user to capture the important areas. Table 6 summarises the ratings of the three scans of the same PDB. The DDY value is the same for all three scans while the Homogeneity value shows a very high value for "Scan 1". Therefore the coefficient of variation indicates an unacceptable high variance of the three ratings. The assessment by the BDA software is acceptable and the rating by DDY is perfect, because there are no deviations.



Barrier Scan 1 Scan 2 Scan 3

Figure 5.9: FIMCAR Supermini 2 PDB scans of the same barrier

Table 6: Comparison of metric assessments of FIMCAR Supermini 2 scans of the same barrier.

	PPS	Homogeneity value	DDY
Scan 1	4.8	122,006,265.00	0.6
Scan 2	3.5	38,180,200.00	0.6
Scan 3	4.1	41,828,238.00	0.6
Mean value	4.1	67,338,234.33	0.6
Median value	4.1	41,828,238.00	0.6
Coefficient of Variation	15.7	70.4	0.0

5.2.2 Conclusions R&R Analysis

Repeatable results were obtained in terms of vehicle performance, pulse and intrusions. The A-Pillar intrusions were below 5 mm for all three tests, the same range of A-Pillar intrusions in a Euro NCAP test.

A correct activation of the Safety Restraint System (SRS) was achieved in two of the three tests. In those cases the dummy injuries were well below R94 limits, repeatable results in terms of dummy values when a correct activation of the SRS was observed.

The R&R analysis of the metric assessments shows that the DDY metric is very robust in analysing barrier footprints of the same vehicle. It needs to be checked if the deviation of "Test 2 @ Lab 1" depends on the wrong horizontal overlap. The BDA software and the Homogeneity value seem not to be capable of fulfilling R&R requirements because the computed values differ too much. In terms of the PPS the assessments mainly depend on the intrusion depths. A review of the rating corridors for the intrusion depth is proposed.

6 CONCLUSIONS

In regards to the off-set test procedure, FIMCAR decided to propose the current R94 test procedure (without additional compatibility metrics) as FIMCAR's off-set test approach. The test will include additional structural requirements to ensure the passenger compartment stability during the crash test. Therefore, an equivalent test to the current ODB (R94) will be proposed for the off-set test procedure.

Because of the potential of the PDB to include compatibility metrics, WP2 has continued the PDB metric development until the end of FIMCAR project. The development focused on the assessment of the load spreading issue, which was defined as a Priority 1 issue by FIMCAR consortium.

The fundamentals of the assessment method using the PDB off-set test were defined in D2.1 [Lazaro 2013]. Different metrics have been investigated for assessing compatibility issues. The recently investigated metrics have shown reasonably good results in terms of correlation with a subjective assessment. The proposed metric is based on the DDY criterion which is a vehicle mass independent criterion. It is calculated from the PDB barrier's deformations. More specifically, it calculates the barrier's slope in the lateral (Y) direction and penalizes vehicles producing high slopes such as those occurring at the edges of holes. However, the metric still needs to be developed further and validated.

The full scale tests performed in WP2 shown that the PDB represents a reasonable severe test compared to the Euro NCAP test, which is considered the reference today in Europe. The vehicle pulse and dummy values measured in the tests performed in WP2 shown comparable results to the Euro NCAP reference. Further validation is needed for vehicles with masses over 2000 kg.

Finally, R&R issues have been analysed for the PDB test procedure. The study was conducted using the FIMCAR Supermini 2 PDB data. Three different tests were performed in two different FIMCAR laboratories showing repeatable results.

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8 GLOSSARY

ATD:	Anthropomorphic Test Device
AoI:	Area of Interest
CIZ:	Common interaction zone (as described in Part581 zone)
EES:	Estimate Equivalent Speed
EEVC:	European Enhanced Vehicle Safety Committee
Euro NCAP:	European New Car Assessment Programme
FW:	Full Width Frontal Impact
HIII:	Hybrid III test dummy
ODB:	Off-set Deformable
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PEAS:	Primary Energy Absorbing Structures
PDB:	Progressive Deformable Barrier
PPS:	Partner Protection Score (assessment result of BDA and PDB software)
R&R:	Repeatability and Reproducibility
SDI:	Smooth Deformation Index
SEAS:	Secondary Energy Absorbing Structures
SRS:	Safety Restraint System
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility

ANNEX A: OFF-SET TEST AND ASSESSMENT PROTOCOL

TEST CONFIGURATION

In this annex the off-set test procedure proposed by FIMCAR is described. The deformable element of the trolley corresponds to the current UN-ECE-Regulation 94 test as well as impact speed and overlap taken into account the FIMCAR aim to at least maintain the current level of compartment strength. The addition of a requirement for A-pillar deformations to be less than 50 mm will guarantee sufficiently strong occupant compartments by enforcing the stability of the forward occupant cell. There is no explicit requirement for compartment stability in the current UN-ECE Regulation 94 that ensures a minimum level for Europe. Euro NCAP tests tend to promote stronger compartment designs than R94 but this is not a mandatory test.

The text reproduced below was prepared by FIMCAR in order to add intrusion requirements to the existing ECE-R 94.

CHANGES TO ECE-R 94

Chapter 5.2.8. (new)

The rearward movement of the A-post shall not be more than 50 mm

Annex 11 (new)

Intrusion Measurements

8.1 Before test

8.1.1 Remove the carpet, trim and spare wheel from the luggage compartment. The plastic trim or rubber seals that might influence the latching mechanism should be re-fitted once the intrusion measurements have been recorded. This is to ensure that any opening of the rear door during the impact is not caused by the omission of some part of the trim around the latching mechanism.

8.1.2 Locate the vehicle axis reference frame (see Figure A-1) centrally to the rear of the vehicle.

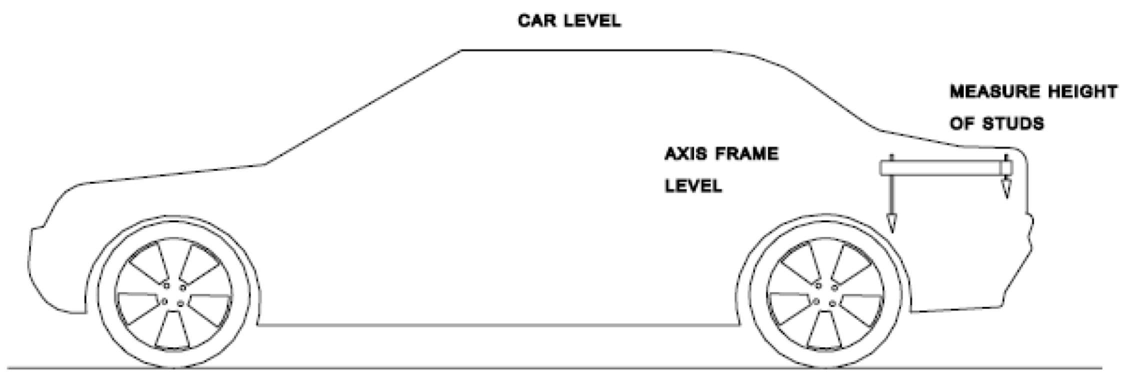


Figure A-1: Setting up axis reference frame.

8.1.3 Level the reference frame

8.1.4 Measure and record the stud heights of the reference frame. These will be used after the test to help reset the reference frame, if required.

8.1.5 If it is necessary to lean on the vehicle to reach the following points, the vehicle should be supported to maintain the ride heights during measuring.

8.1.6 Set up the vehicle co-ordinate axes in the 3D arm or similar device.

8.1.7 Mark and record the position of at least 5 datum points on the rear of the vehicle. These points should be on structures which are not expected to be deformed in the test and should be positioned such that they have wide spaced locations in three dimensions and can all be reached with the 3D measuring system in one position.

8.1.8 Working on the passenger side of the vehicle determine and mark the positions of the A-post which are
i) at a distance of 100 mm above the sill
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

8.1.9 All points should be as close as possible to the rubber sealing strip around the door aperture.

8.1.10 Measure and record the pre-impact positions of the two aperture points.

8.1.11 Working on the driver's side of the vehicle determine and mark the positions on the A-post which are
i) at a distance of 100 mm above the sill
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

8.1.12 All points should be as close as possible to the rubber sealing strip around the door aperture.

8.1.13 Measurement should be taken of the pre-impact positions of the door aperture points.

8.1.14 After test

8.1.15 Use any 3 of the 5 datum points at the rear of the vehicle, and their pre-impact measurements, to redefine the measurement axes.

8.1.16 If the axes cannot be redefined from any 3 of the datum points relocate the axis reference frame in the same position as in section 8.1.4. Set the studs of the frame to the same heights as in section 8.1.7 (Figure A-2). The frame should now be in the same position relative to the car as it was before impact. Set up measurement axes from the frame.

8.1.17 Record the post-impact positions of the B-post points on the passenger's side of the vehicle.

8.1.18 Compare the vertical co-ordinate of the B-post sill point before (section 8.1.8) and after (section 8.1.16) the test.

8.1.19 Find the angle θ that best satisfies the following equation: $z = -x' \sin\theta + z' \cos\theta$ for the B-post sill point (where z = pre impact vertical measurement and x',z'= post-impact longitudinal and vertical).

8.1.20 Working on the driver's side of the vehicle, record the door aperture points.

8.1.21 Transform the post impact longitudinal and vertical measurement (x',z') using the following equations.

$$\begin{pmatrix} X' \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} x' \\ z' \end{pmatrix}$$

8.1.22 Where ϑ is the angle determined in Section 8.1.19. X and Z should now be in the same frame of reference as the pre-impact measurements. [1]

8.1.23 From the pre-impact and adjusted post-impact data collected, determine the rearward movement of the A-post at waist level

8.1.24 Record these intrusion measurements in the test details.

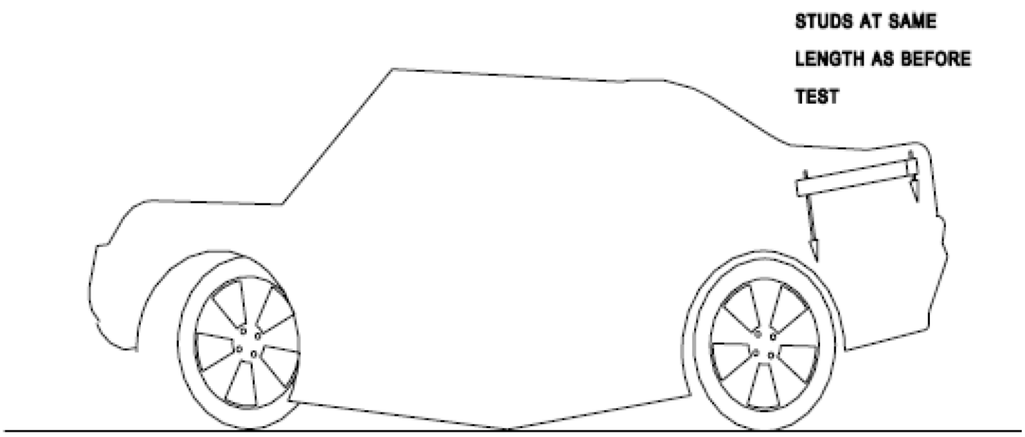


Figure A-2: Re-setting axis reference frame after test.

[1] This assumes that the point on the passenger B-post sill is not displaced vertically or laterally during the impact.

ANNEX B: PBD TEST SEVERITY

The definition of an appropriate severity level is crucial for any test procedure. According to the FIMCAR strategies, one of the boundary conditions to be considered for the definition of the test severity is that the current level of compartment strength shall not be reduced. The off-set test is the main candidate to assess compartment strength as it loads the structures only on one side of the vehicle. According to the FIMCAR goals, ECE R94 requirements were set as the reference.

In the literature, the severity level in an off-set test procedure was often expressed in EES or, in other words, the deformation energy dissipated by the test vehicle. However, EES calculation, especially for the ODB (ECE R94 and Euro NCAP) is based on various assumptions (e.g., constant energy dissipated by the barrier face independent of the test vehicle, rotational energy after the impact was neglected etc.). Furthermore the deformation energy does not necessarily reflect the requirements for the cabin strength. NHTSA analysed one car with different front structures tested in the PDB procedure. While the older one without advanced energy absorbing structures did not show any reduction in the door opening (i.e., A-pillar deformation) a small reduction in the door opening was observed the newer model. In contrast the calculated EES was slightly higher in the older car [Meyerson 2009].

To investigate the severity of an offset test, in particular the PDB test, several sources for the analysis of severity level were explored by FIMCAR.

COMPARISON OF TEST SEVERITY BY TESTS

In general the PDB aims at harmonising the severity level amongst vehicles of different masses. With the current barrier face the test severity increases with mass as the energy absorbed by the deformable element does linearly increase with the test weight, see Figure B-1.

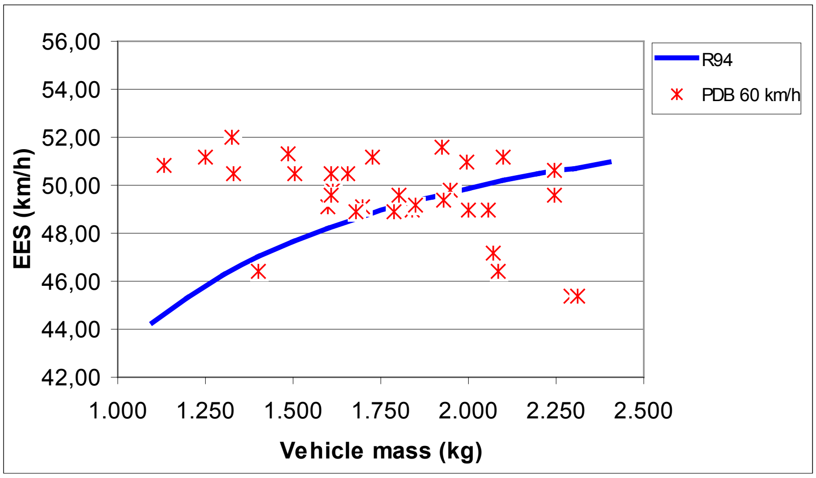


Figure B-1: Estimated EES in R94 and calculated EES in PDB tests [Lazaro 2013].

However, as the assumptions that lead to the EES estimation for the ECE R94 curve and the calculated PDB points may be misleading and cabin intrusion were compared.

UTAC analysed mean intrusion and mean acceleration in different left hand drive and right hand drive cars in ECE R94 tests, R94 tests with an increased test speed of 60 km/h (instead of 56 km/h) and PDB tests [Delannoy 2005]. Although the difference (between R94 and PDB) in mean intrusion was decreasing with the vehicle's weight up to approx. 1.750 kg, mean intrusion of the ECE R94 was at least almost maintained in the PDB tests, Figure B-2. Interestingly mean acceleration was significantly higher in all PDB tests independently of the test weight.

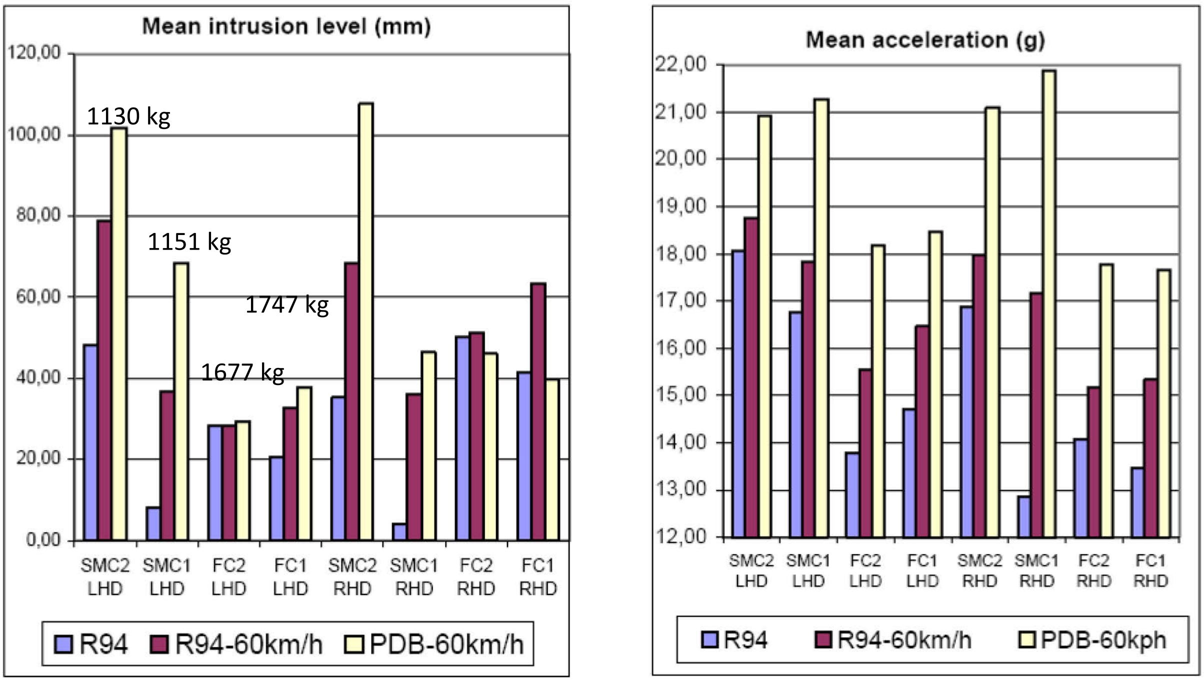


Figure B-2: Comparison of mean intrusion and mean acceleration in ECE R94, ECE R94 with increased test speed and PDB tests [Delannoy 2005].

Finally FIMCAR analysed published crash test data from the US to compare PDB and ECE R94 test conditions. Subject of the analysis were

- maximum cabin acceleration,
- mean cabin acceleration,
- intrusion at dashboard,
- intrusion at door waist level,
- intrusion at door sill level,
- intrusion in foot area.

For most of the cars, except the Ford FT250, intrusion was larger or equal in the PDB tests, see Figure B-3. As the FT250 is a body on frame vehicle, which is more like a truck than a passenger car, the results here are somehow irrelevant.

					Acceleration [G]		Intrusion [mm]			
Vehicle	Test Weight	LLP	Load case	Comments	Max	Mean	Dash	Door Waist	Door Sill	Foot area
Chevrolet Aveo	1433kg	NO	R94	ODB barrier bottoms out	28,7	8,9	52	62	5	38
			PDB		31,2	9,5	65	80	7	52
Ford Escape	1781kg	NO	R94	ODB barrier bottoms out	30,0	9,0	14	13	2	37
			PDB	Rupture / separation in barrier face	25,5	9,2	42	34	-1	42
Ford 500	1916kg	YES	R94	ODB barrier bottoms out	22,9 19,3 21,5	9,1 8,2 8,9	21 10 16	14 - 10	5 1 2	11 4 4
			PDB	Main rail penetrates PDB barrier	24,9 25,5 25,8	8,9 9,1 9,5	16 26 41	16 12 25	5 3 10	3 3 8
Saturn Outlook	2408kg	YES	R94	ODB barrier bottoms out	25,6	8,9	5	1	1	2
			PDB	Main rail penetrates PDB barrier	24,9	9,1	2	1	0	-1
Ford F250	3291kg	NO	R94	ODB barrier bottoms out	-	-	-	49 42	20 39	
			PDB	Main rail penetrates PDB barrier	-	-	-	12	3	

Key:

significantly better　　significantly worse　　no significant difference

tendency to be better but large scatter　　tendency to be worse but large scatter

Figure B-3: Comparison of acceleration and intrusion for PDB and ECE R94 tests.

As the test results show a blurred picture FIMCAR decided to add simulation activities to this analysis.

COMPARISON OF TEST SEVERITY BY SIMULATION

For the comparison of test severity between ECE R94 and PDB the Generic Car Models and a model of an actual SUV were used.

Advantages of modelling compared to testing are that the energy calculation is much more accurate and that intrusions can be measured dynamically and again more accurate. Furthermore it is possible to measure the loads applied to different parts of the models using concepts in the software called “section forces”.

The Generic Car Models GCM1A, GCM1B, GCM2A, GCM2B and GCM3 [Stein 2013] were used to compare average intrusion into the cabin, steering wheel intrusion, EES and max cabin acceleration for ECE R94 and PDB tests. Cabin intrusion is significantly higher in the PDB tests for the lighter models while it is smaller for the heavier models, see

Figure B-4 and Figure B-5. A similar trend but with smaller relative difference is visible for EES, see

Figure B-4. For the cabin acceleration no clear trend is visible.

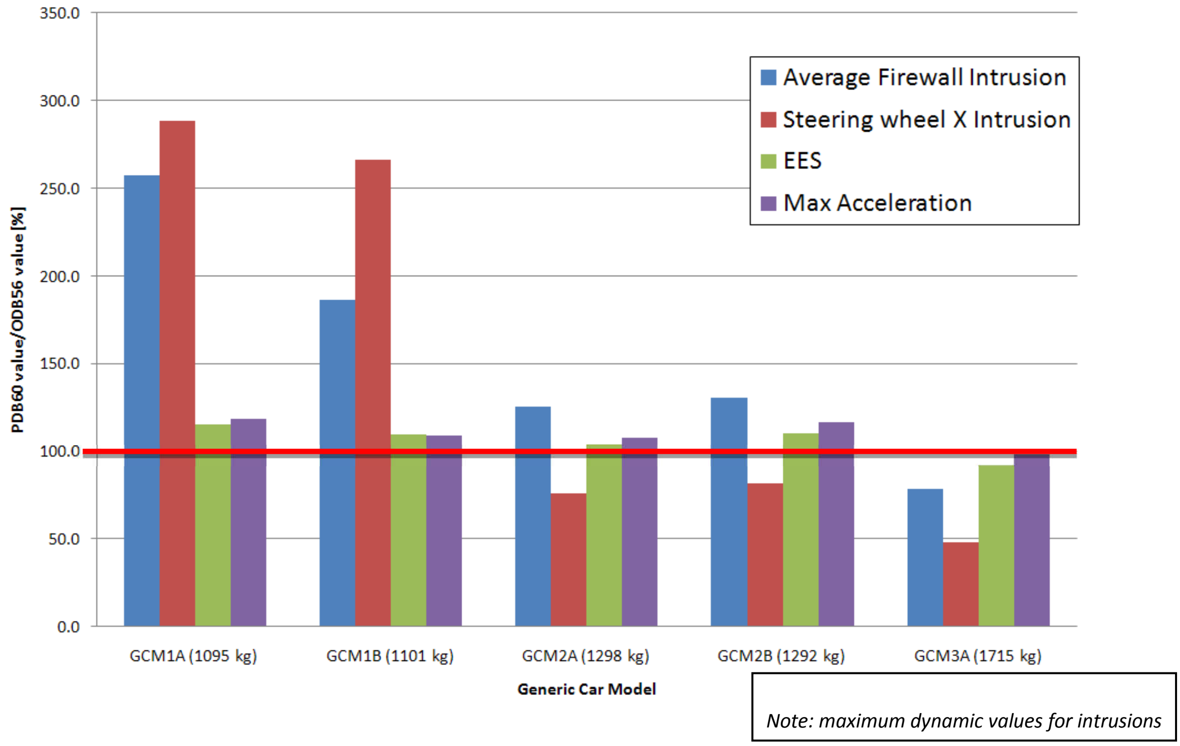


Figure B-4: Cabin intrusion, EES and acceleration for ECE R94 and PDB on GCM.

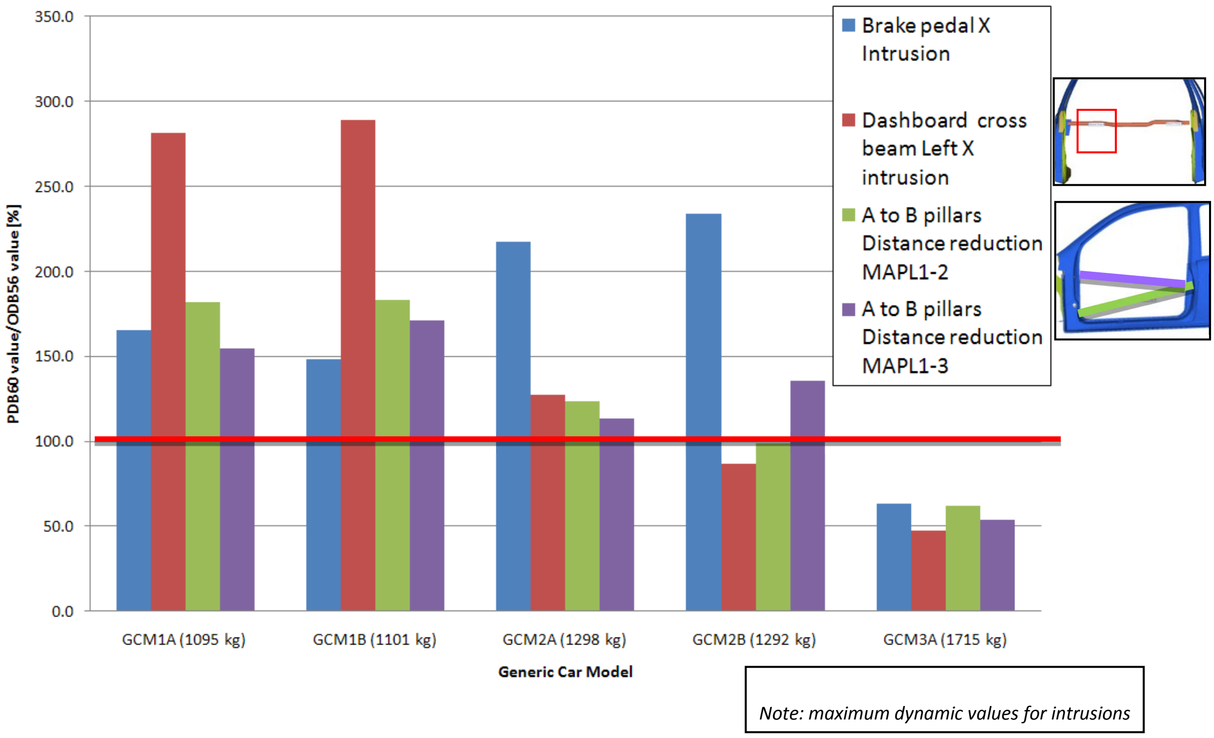
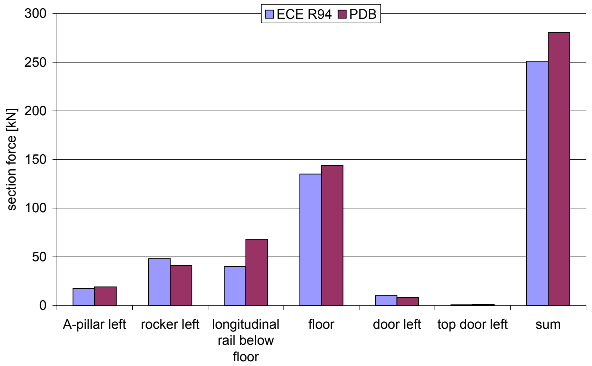
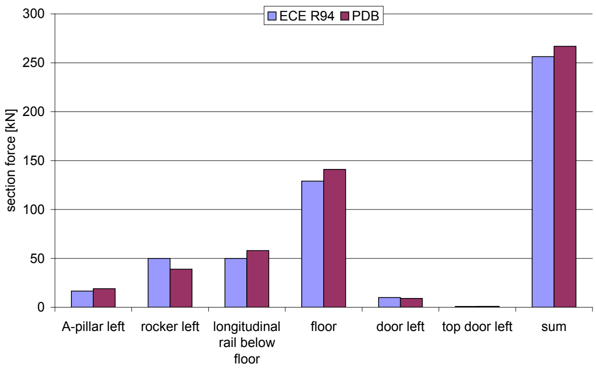


Figure B-5: Cabin intrusion at different locations for ECE R94 and PDB on GCM.

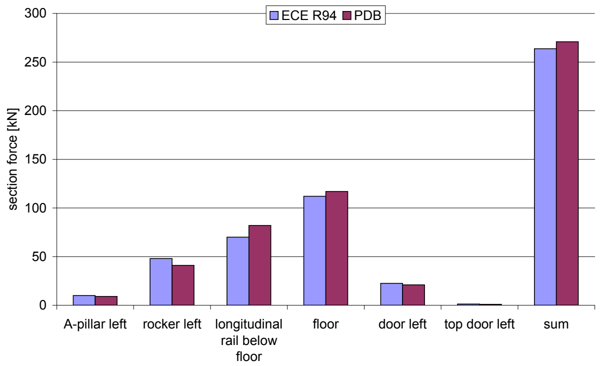
The comparison of section forces using the Generic Car Models show higher section forces and thus higher cabin loading in the ECE R94 test for lighter models and smaller section forces for the heavier ones. Another interesting aspect is that the section forces increase in the ODB test with a second load path (GCM1B and GCM2A) while in the PDB test it is the other way round, see Figure B-6.



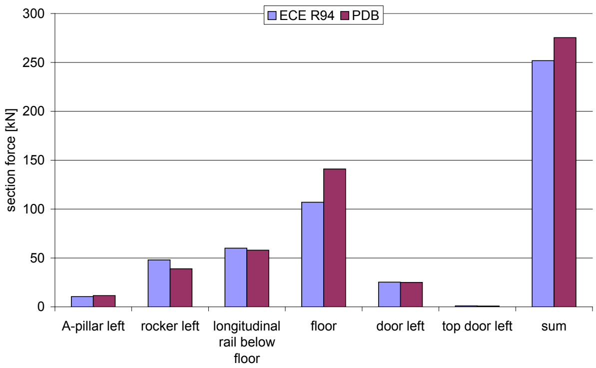
GCM1A



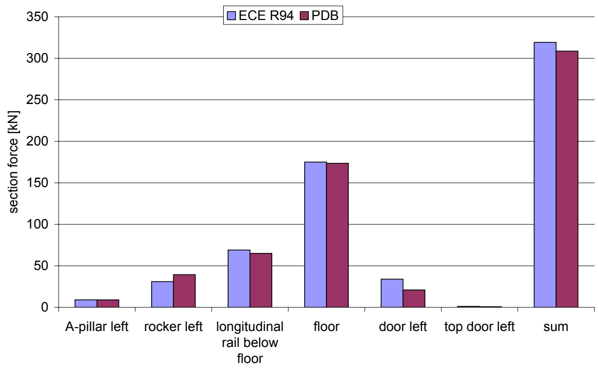
GCM1B



GCM2A



GCM2B



GCM3

Figure B-6: Section forces for ECE R94 and PDB on GCM.

Finally a model of an actual SUV was analysed. As the model showed a crossbeam failure that would likely result in failing of PDB metrics the model was improved to avoid the failure. Firewall intrusion of this 2.2 t car is larger in the ECE R94 tests, see Figure B-7.

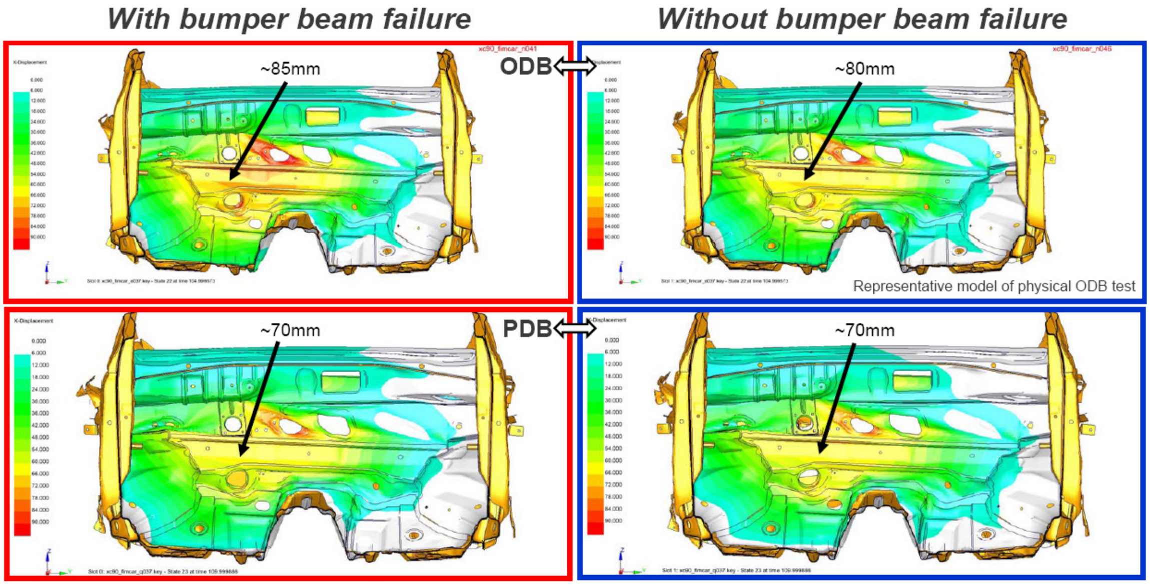


Figure B-7: Comparison of firewall intrusion in actual SUV model.

In summary the simulation results show a clear tendency of decreasing requirements for the PDB test with vehicle weight, see Figure B-8.

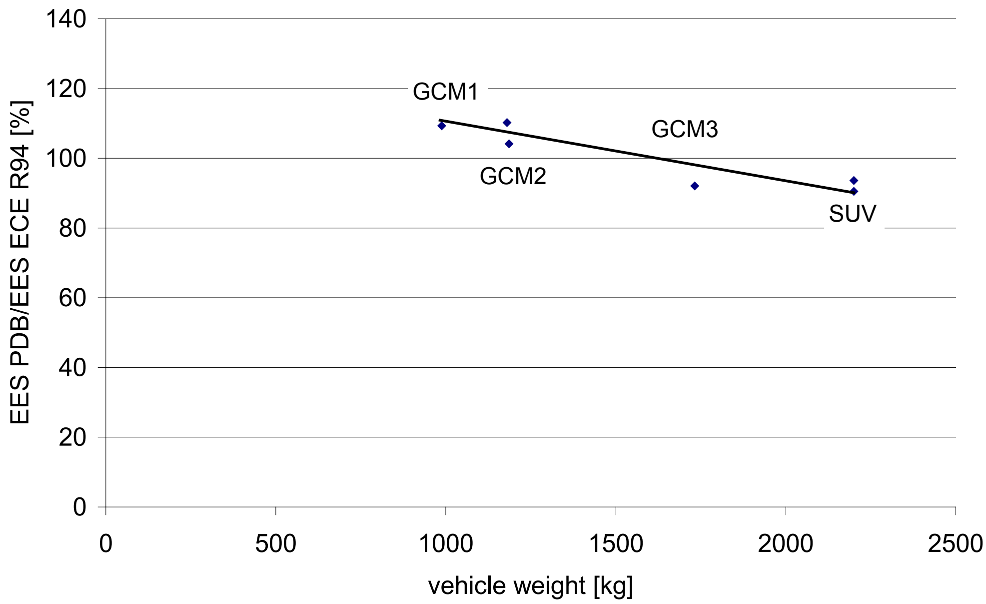


Figure B-8: EES dependency on vehicle weight.

CONCLUSION

According to the FIMCAR Deliverable D1.1 compartment strength issues in accident data mainly occur in car-to-HGV and car-to-object accidents. Furthermore compartment strength issues are not an isolated problem of small cars. That means that the car-to-barrier test for the assessment of compartment strength should somehow reflect this situation.

Most of the data presented indicate that the requirements for compartment strength are decreasing with vehicle weight when using a PDB test.

ANNEX C: PDB DEFINITION AND CERTIFICATION

CHARACTERISTICS OF THE DEFORMABLE BARRIER

The PDB deformable barrier is a stacking of three deformable aluminium honeycomb cores. The first (front deformable core, 250 mm thick) is designed to provide a constant load in depth. The second (progressive deformable core, 450 mm thick) is designed to provide a progressive load in depth. The third (back deformable core, 90 mm thick) is designed to provide a constant load in depth. Aluminium honeycomb cores are bonded together with different aluminium sheets forming a ready to use deformable barrier to be fixed on a rigid surface (wall, trolley).

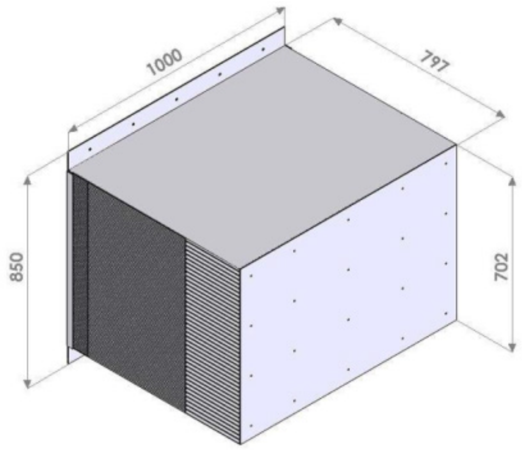


Figure C-1: PDB Barrier dimensions.

1. COMPONENT AND MATERIAL SPECIFICATIONS

The dimensions of the barrier are illustrated in Figure C-1 of this annex. The dimensions of the individual components of the barrier are listed separately below.

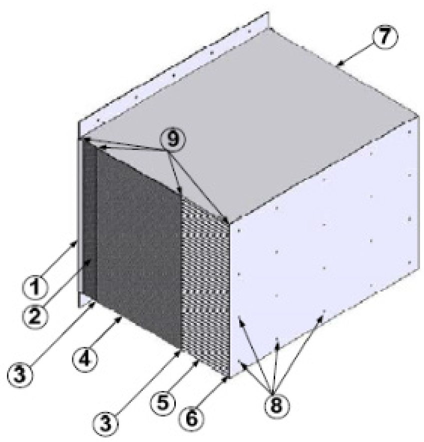


Figure C-2: PDB Barrier components.

The PDB barrier is composed of the following components:

(1) One back plate,

(2) One back deformable core,

(3) Two intermediate plates,

(4) One progressive deformable core,

(5) One front deformable core,

(6) One contact plate,

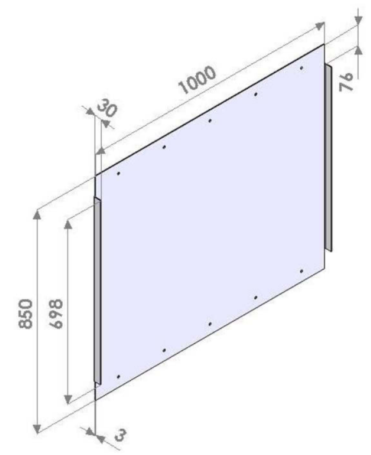
(7) One outer cladding,

(8) Blind rivets,

(9) Epoxy resin.

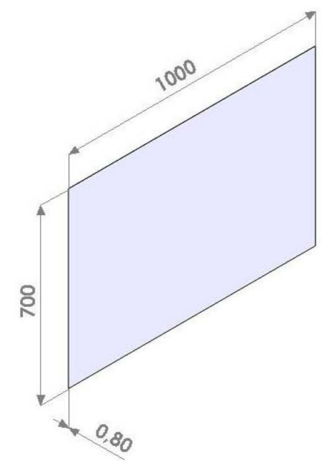
1.1. Back Plate geometrical and material characteristics (1)

The back plate is 1000 ± 2.5 mm wide and 850 ± 2.5 mm high. The thickness is 3 mm. The back plate is manufactured from Aluminium of 1050A H14.



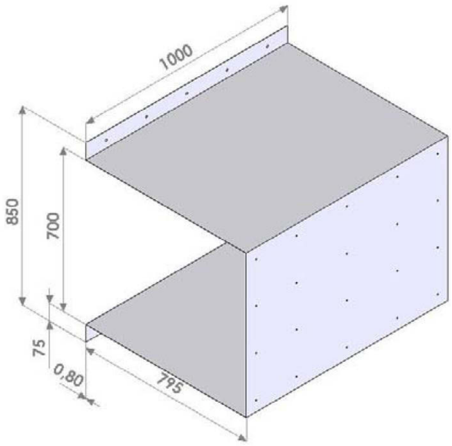
1.3. Contact plate geometrical and material characteristics (6)

The contact plate is 1000 ± 2.5 mm wide and 700 ± 2.5 mm high. The thickness is 1.5 mm. The contact plate is manufactured from Aluminium of 1050A H24.



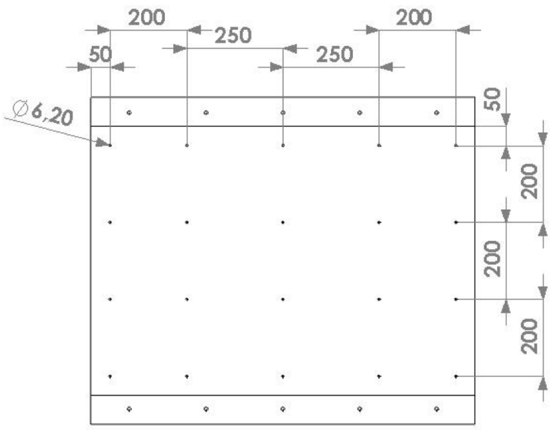
1.4. Cladding geometrical and material characteristics (7)

The cladding is 1000 ± 2.5 mm wide and 850 ± 2.5 mm high. The thickness is 0.8 mm. The cladding is manufactured from Aluminium of 5754 H22. The cladding has two mounting flanges of 75 mm allowing rigid wall mounting. Twenty 6.2 mm holes shall be drilled trough the outer cladding in order to accommodate front face blind rivets.



1.5. Rivets position (8)

Twenty blind rivets shall be used to improve the link between outer cladding and contact plate. Rivets shall be aluminium/steel blind rivets diameter 6 mm.



1.6. Adhesive (9)

The adhesive to be used shall be an Epoxy Resin type H9940 or equivalent.

1.7. Honeycomb deformable cores

Geometrical and material characteristics:

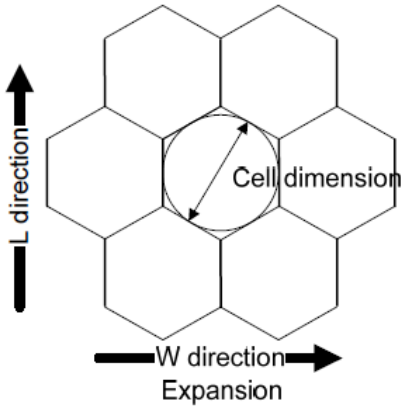
The PDB deformable barrier is a stacking of three deformable aluminium honeycomb cores and provides 4 different crushing strength areas (#1, #2, #3, #4) whose forms and positioning are shown below.

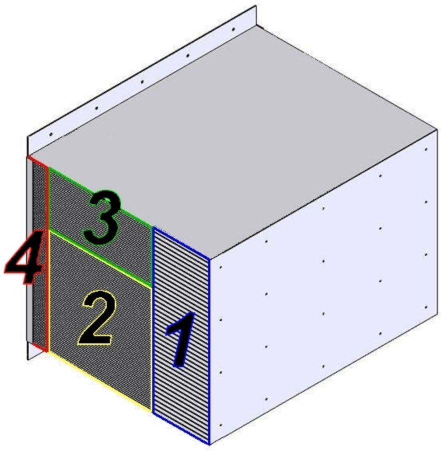
All honeycomb deformable cores shall be made of 3003 aluminium.

(a) The cell dimensions for the front block shall be 19.1 mm ± 15 percent.

(b) The cell dimensions for the intermediate block shall be 9.5 mm ± 15 percent.

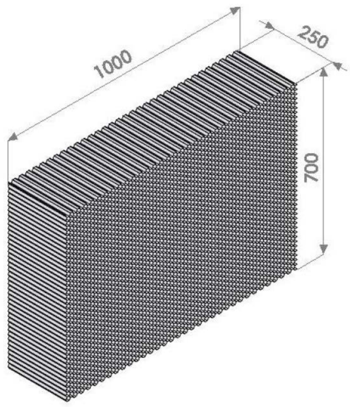
(c) The cell dimensions for the rear block shall be 6.3 mm ± 15 percent.





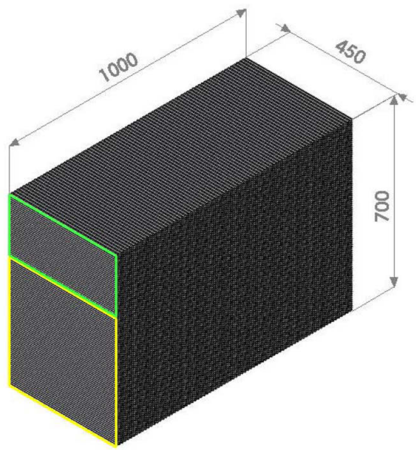
1.7.1. Front block (5)

The front block (area #1) shall be 700 ± 5 mm in L Direction, 1000 ± 5 mm in W direction and 250 ± 1 mm in T direction. The crushing characteristics of the front block are constant.



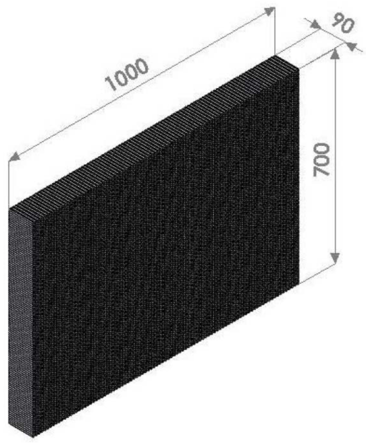
1.7.2. Progressive block (4)

The progressive block (area #2 and #3) shall be: 700 ± 5 mm in L direction, 1000 ± 5 mm in W direction and 450 ± 1 mm in T direction. The crushing characteristics of the progressive block present 2 different load paths. The lower load path #2, offers a progressive resistance in depth for first 350 mm and a constant resistance in depth for last 100 mm. The upper load path #3, offers a progressive resistance in depth for first 350 mm and a constant resistance in depth for last 100 mm.



1.7.3. Back block (2)

The back block (area #4) shall be 700 ± 5 mm in L direction, 1000 ± 5 mm in W direction and 90 ± 1 mm in T direction. The crushing characteristics of the front block are constant.



2. ALUMINIUM HONEYCOMB CERTIFICATION

The aluminium honeycomb blocks should be processed such that the force deflection-curve when statically crushed (according to the procedure defined below) is within the corridors defined for each of the three blocks. Samples taken from each batch of processed honeycomb core shall be tested.

2.1. Sample size

One sample for the front block (area #1): The sample size of the aluminium honeycomb for static tests shall be 200 mm in W direction x 200 mm in L direction x 250 mm in T direction for the front block.

Two samples for the progressive block: One sample for lower load path (area #2) and one sample for upper load path (area #3). The samples size of the aluminium honeycomb for static tests shall be at least 100 mm in W direction x 100 mm in L direction x 450 mm in T direction for the progressive block.

One sample for the back block (area #4): The sample size of the aluminium honeycomb for static tests shall be 100 mm in W direction x 100 mm in L direction x 90 mm in T direction for the back block.

2.2. Data collection and crush rate

The samples should be compressed between two parallel loading plates which are at least 20 mm larger than the block cross section. The compression speed shall be 100 mm/min, with a tolerance of 5 percent. The data acquisition for static compression shall be sampled at a minimum of 5 Hz. The static test shall be continued until the block compression is at least 80 percent of honeycomb core initial thickness.

2.3. Sample crush strength specification

The crush resistance curve for each block tested shall be included within the corridors defined below:

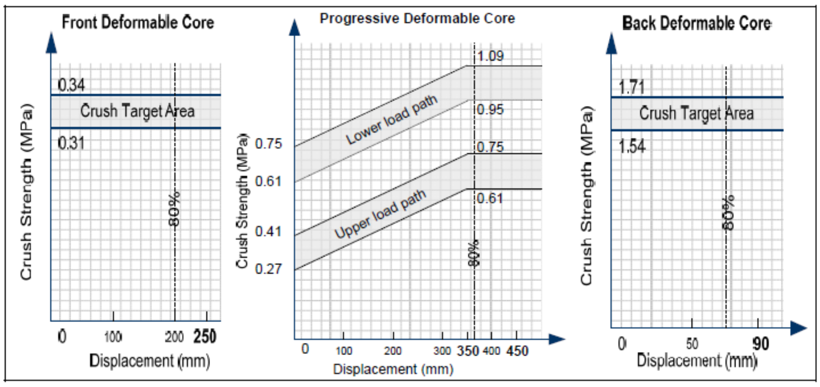


Figure C-2: Crush strength specification for the different cores.

3. ADHESIVE BONDING PROCEDURE

3.1. Immediately before bonding, aluminium sheet surfaces to be bonded shall be thoroughly cleaned using a suitable cleaning and degreasing solution**.** This is to be carried out as required to eliminate grease or dirt deposits. The cleaned surfaces shall then be abraded using 120 grit abrasive paper. Metallic/Silicon Carbide abrasive paper is not to be used. The surfaces shall be thoroughly abraded and the abrasive paper changed regularly during the process to avoid clogging, which may lead to a polishing effect. Following abrading, the surfaces shall be thoroughly cleaned again, as above. All dust and deposits left as a result of the abrading process shall be removed, as these will adversely affect bonding.

3.2. The adhesive should be applied to one surface only. In cases where honeycomb is to be bonded to aluminium sheet, the adhesive should be applied to the aluminium sheet only. A maximum of 0.5 kg/m2 shall be applied evenly over the surface, giving a maximum film thickness of 0.5 mm.

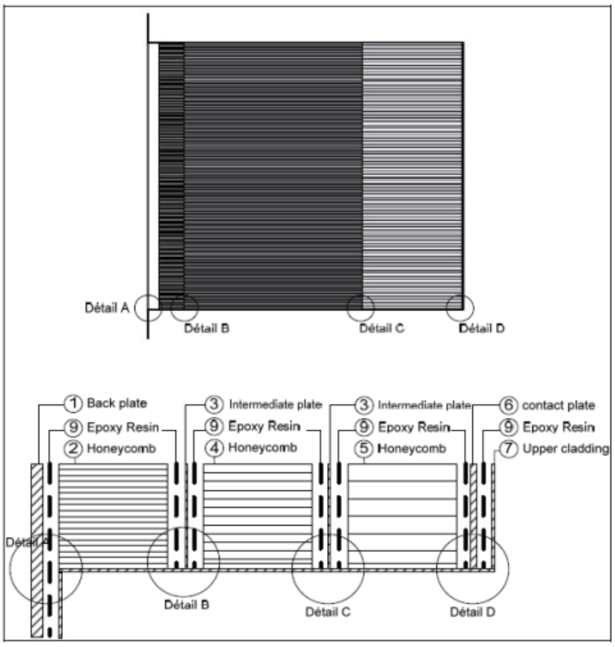


Figure C-3: Gluing detail among the different parts.

4. CONSTRUCTION

4.1. The main honeycomb blocks shall be bonded to the sheets with adhesive such that the cell axes are perpendicular to the sheets. The outer cladding shall be bonded to the contact plate. The upper and lower surfaces of the outer cladding sheet shall not be bonded to the honeycomb blocks but should be positioned closely to it. The cladding sheet shall be adhesively bonded to the back plate at the mounting flanges.

4.2. Clearance holes for mounting the barrier are to be drilled in the mounting flanges (shown in Figure C-4). The holes shall be of 9.5 mm diameter. Five holes shall be drilled in the top flange at a distance of 40 mm from the top edge of the flange and five in the bottom flange, 40 mm from the bottom edge of that flange. The holes shall be at 100 mm, 300 mm, 500 mm, 700 mm, and 900 mm from either edge of the barrier. All holes shall be drilled to ± 1 mm of the nominal distances. These holes locations are a recommendation only. Alternative positions may be used which offer at least the mounting strength and security provided by the above mounting specifications.

5. MOUNTING

5.1. The deformable barrier shall be rigidly fixed to the edge of a mass of not less than 7×10^4 kg or to some structure attached thereto. The attachment of the barrier face shall be such that the vehicle shall not contact any part of the structure more than 75 mm from the top surface of the barrier (excluding the upper flange) during any stage of the impact. The front face of the surface to which the deformable barrier is attached shall be flat and continuous over the height and width of the face and shall be vertical ± 1° and perpendicular ± 1° to the axis of the run-up track. The attachment surface shall not be displaced by more than **2** mm during the test. If necessary, additional anchorage or arresting devices shall be used to prevent displacement of the stationary barrier structure. The edge of the deformable barrier shall be aligned with the edge of the stationary barrier structure appropriate for the side of the vehicle to be tested.

5.2. The deformable barrier shall be fixed to the block by means of ten bolts, five in the top mounting flange and five in the bottom. These bolts shall be of at least 8 mm diameter. Steel clamping strips shall be used for both the top and bottom mounting flanges (see Figures C-3). These strips shall be 60 mm high and 1000 mm wide and have a thickness of at least 3 mm. The edges of the clamping strips shall be rounded-off to prevent tearing of the barrier against the strip during impact. The edge of the strip shall be located no more than 5 mm above the base of the upper barrier-mounting flange, or 5 mm below the top of the lower barrier-mounting flange. Five clearance holes of 9.5 mm diameter must be drilled in both strips to correspond with those in the mounting flange on the barrier (see paragraph 4.). The mounting strip and barrier flange holes may be widened from 9.5 mm up to a maximum of 25 mm in order to accommodate differences in back-plate arrangements and/or load cell wall hole configurations. None of the fixtures shall fail in the impact test. In the case where the deformable barrier is mounted on a load cell wall (LCW) it shall be noted that the above dimensional requirements for mountings are intended as a minimum. Where a LCW is present, the mounting strips may be extended to accommodate higher mounting holes for the bolts. If the strips are required to be extended, then thicker gauge steel should be used accordingly, such that the barrier does not pull away from the wall, bend or tear during the impact. If an alternative method of mounting the barrier is used, it should be at least as secure as that specified in the above paragraphs. **The ground clearance of the front part of the barrier shall be 150 mm.**

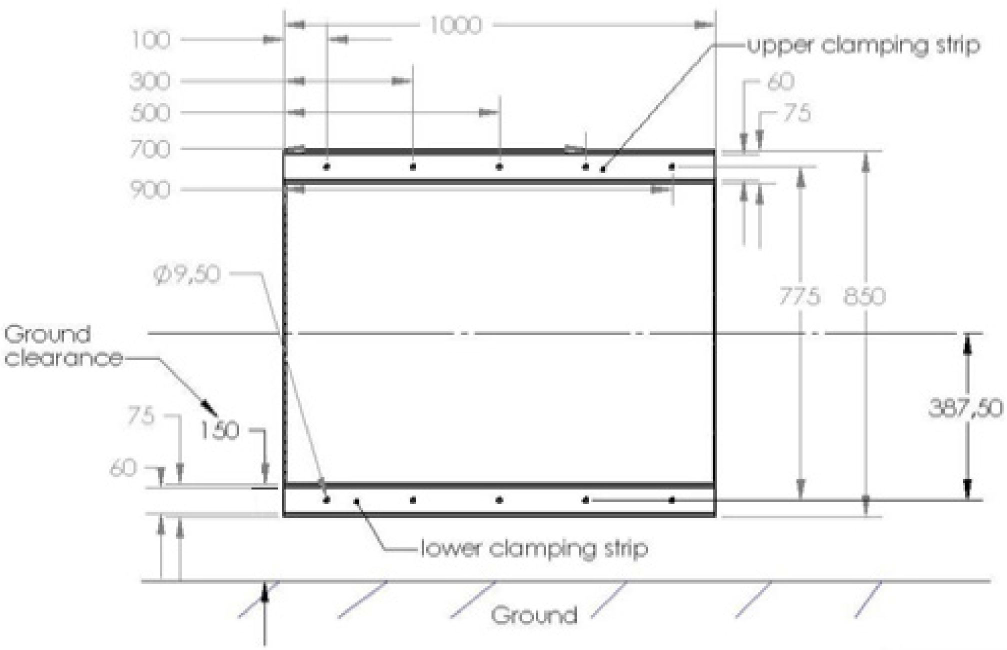


Figure C-4: barrier mounting and ground clearance.

6. CONFORMITY

For every year or 100 barriers faces produced, the manufacturer shall make two dynamic tests according to the method described below:

6.1. Test 1: Rigid wall impactor

6.1.1. Characteristics of the mobile barrier

6.1.1.1. The total mass shall be 1300 kg +/- 30 kg. The trolley shall be so constructed that no permanent deformation appears after the test. It shall be so guided that, during the impact phase, the deviation in the vertical plane does not exceed 5° and 2° in the horizontal plane.

6.1.1.2. The front and rear track width of the trolley shall be 1,500 ± 10 mm.

6.1.1.3. The wheelbase of the trolley shall be 3,000 ± 10 mm.

6.1.1.4. The centre of gravity shall be situated in the longitudinal median vertical plane within 10 mm, 700 ± 30 mm behind the front axle and 500 ± 30 mm above the ground.
6.1.1.5. The distance between the front face of the impactor and the centre of gravity of the barrier shall be 2,000 ± 30 mm.

6.1.2. Deformable barrier tested. The deformable barrier tested shall be representative of the series production of the barrier.

6.1.3. Attachment of the impactor

6.1.3.1. The impactor shall be firmly attached to the trolley in such a way that no relative displacement occurs during the test.

6.1.3.2. The angle between the longitudinal axis of the rigid wall and the direction of motion of the trolley shall be 0° ± 2°.

6.1.3.3. The impactor consists of a rigid block defined in Figure C-5. The material of the impactor must be in steel. The geometry of the impactor must respect the design in Figure C-5.

6.1.4. Attachment of the deformable barrier. The deformable barrier shall be fixed on a rigid wall as specified in paragraph 5.

6.1.5. Test configuration

6.1.5.1. The rigid wall shall overlap the right side of the barrier face by 700 +/- 20 mm in Y axis (Figure C-6).

6.1.5.2. The velocity of the trolley at the moment of the impact shall be 60 km/h -0/+1 km/h. If the test was performed at a higher impact speed and the test results meet the requirements, the test shall be considered satisfactory.

6.1.6. Measurement to be made on the trolley. The position of the transducers measuring the deceleration of the Centre of Gravity (COG) of the trolley during the impact shall be parallel to the longitudinal axis of the trolley (Channel Frequency Class (CFC) of 180).

6.1.7. Reference curve Global force vs. displacement. This displacement is obtained by integration of the deceleration curve of the COG of the trolley obtained. The global crush force is obtained by the multiplication of the trolley acceleration in CFC of 60 by its mass.

6.1.8. Equivalent method. A dynamometric wall behind the barrier may measure the crush force calculation. The global force shall be calculated by the sum of different load cell wall measurements. The sum shall be processed with a CFC 60 filter.

6.1.9. Certification. The force deflection curves of the barrier tested shall lie within the corridors defined in Figure C-8.

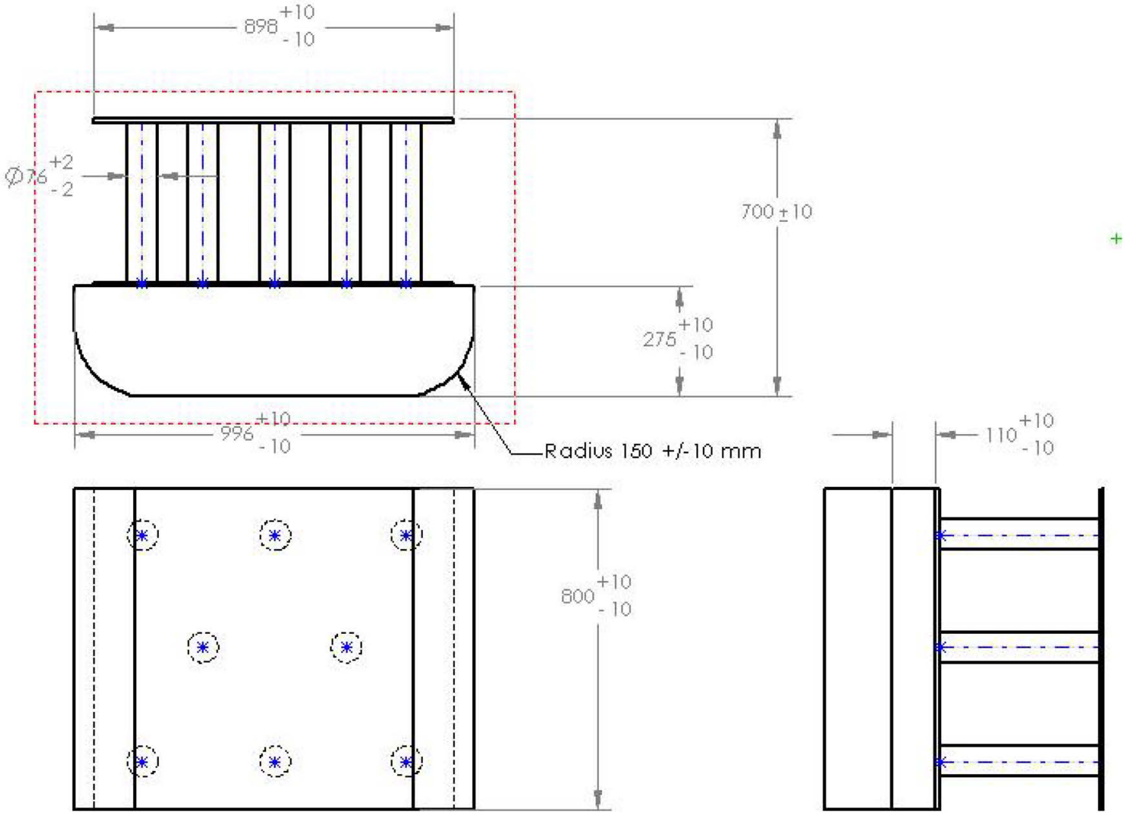


Figure C-5: Engineering drawings flat surface impactor.

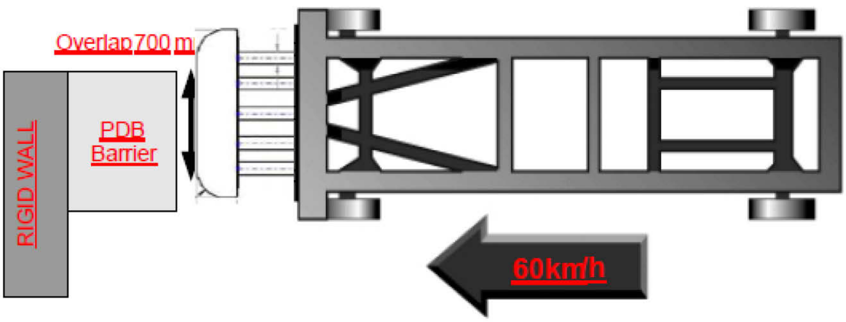


Figure C-6: test configuration flat surface impactor.

Figure C-7: Trolley with impactor.

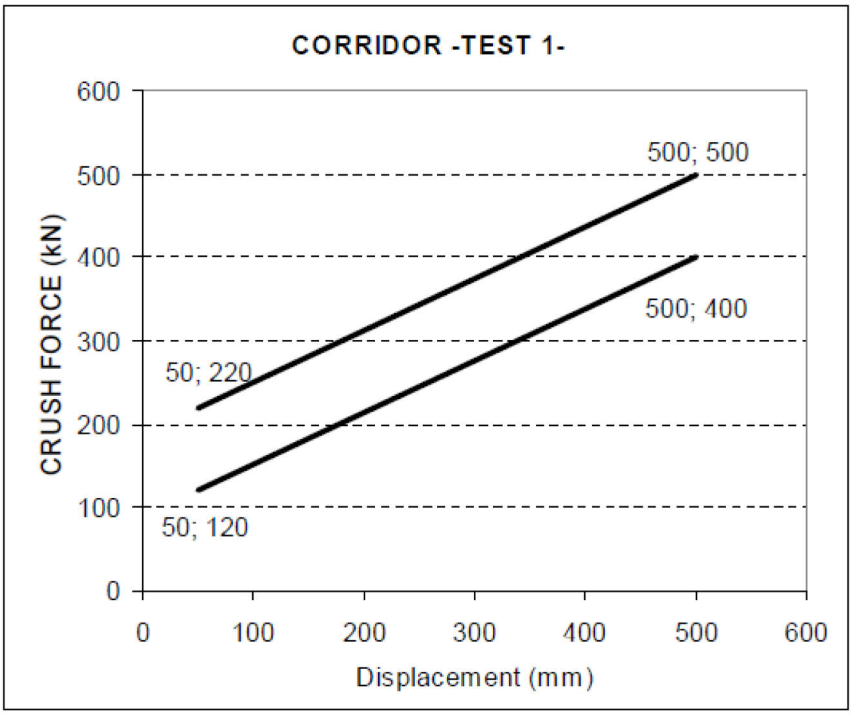


Figure C-8: Corridor.

6.2. Test 2: Rigid tubular impactor

6.2.1. Characteristics of the mobile barrier

6.2.1.1. The total mass shall be 1,300 kg +/- 30 kg. The trolley shall be so constructed that no permanent deformation appears after the test. It shall be so guided that, during the impact phase, the deviation in the vertical plane does not exceed 5° and 2° in the horizontal plane.

6.2.1.2. The front and rear track width of the trolley shall be 1,500 ± 10 mm.

6.2.1.3. The wheelbase of the trolley shall be 3,000 ± 10 mm.

6.2.1.4. The center of gravity shall be situated in the longitudinal median vertical plane within 10 mm, 950 ± 30 mm behind the front axle and 500 ± 30 mm above the ground.

6.2.1.5. The distance between the front face of the impactor and the center of gravity of the barrier shall be 2,100 ± 30 mm.

6.2.2. Deformable barrier tested. The deformable barrier tested shall be representative of the series production of the barrier.

6.2.3. Attachment of the impactor

6.2.3.1. The impactor shall be firmly attached to the trolley in such a way that no relative displacement occurs during the test.

6.2.3.2. The angle between the longitudinal axis of the rigid wall and the direction of motion of the trolley shall be 0° ± 2°.

6.2.3.3. The impactor consists of a rigid block defined in Figure C-9. The material of the impactor must be in steel. The geometry of the impactor must respect the design in Figure C-9.

6.2.4. Attachment of the deformable barrier. The deformable barrier shall be fixed on a rigid wall as specified in paragraph 5.

6.2.5. Test configuration

6.2.5.1. The rigid wall shall overlap the right side of the barrier face by 800 +/- 20 mm in Y axis (Figure C-10).

6.2.5.2. The velocity of the trolley at the moment of the impact shall be 60 km/h -0/+1 km/h. If the test was performed at a higher impact speed and the test results meet the requirements, the test shall be considered satisfactory.

6.2.6. Measurement to be made on the trolley. The position of the transducers measuring the deceleration of the Centre Of Gravity (COG) of the trolley during the impact shall be parallel to the longitudinal axis of the trolley (CFC of 180).

6.2.7. Reference curve Global force vs. displacement. This displacement is obtained by integration of the deceleration curve of the COG of the trolley obtained. The global crush force is obtained by the multiplication of the trolley acceleration in CFC of 60 by its mass.

6.2.8. Equivalent method. A dynamometric wall behind the barrier may measure the crush force calculation. The global force shall be calculated by the sum of different load cell wall measurements. The sum shall be processed with a CFC of 60 filter.

6.3. Validation

6.3.1. The force deflection curves of the barrier tested shall lie within the force corridors defined in Figure C-12.

6.3.2. The barrier face deformation shall lay within the deformation defined in Figure C-13.

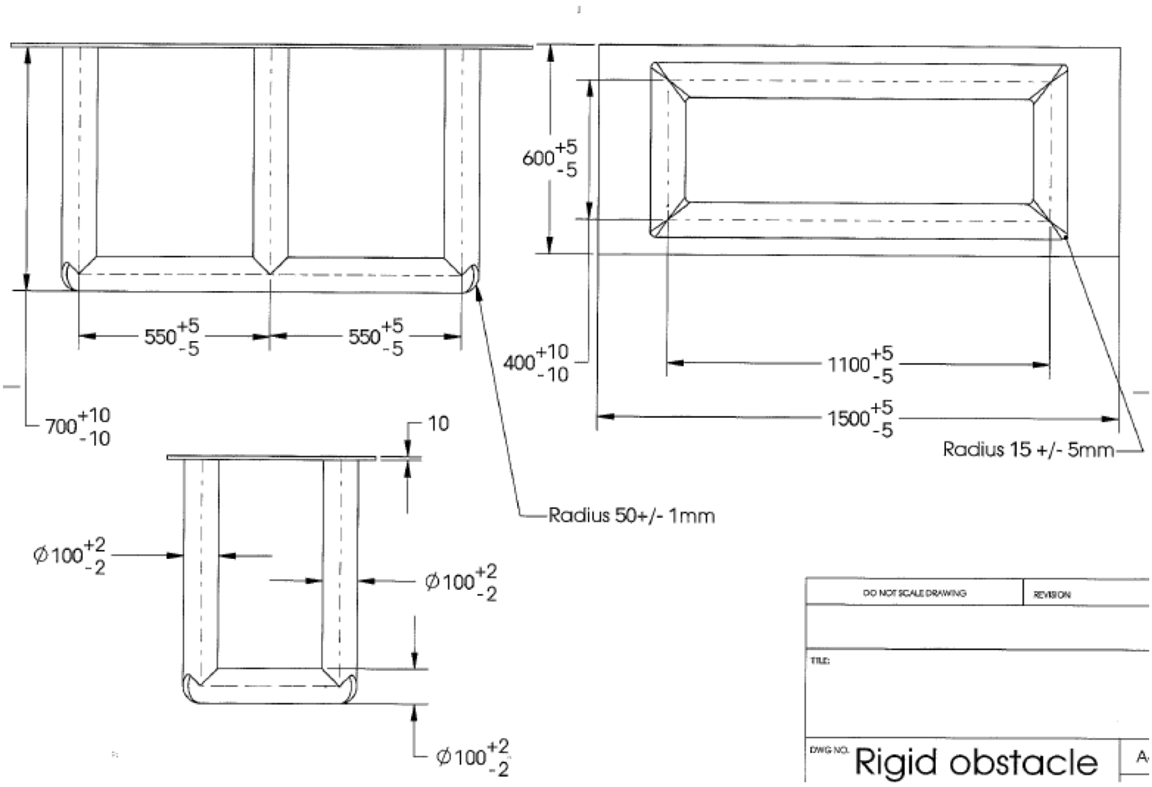


Figure C-9: Engineering drawing tube impactor.

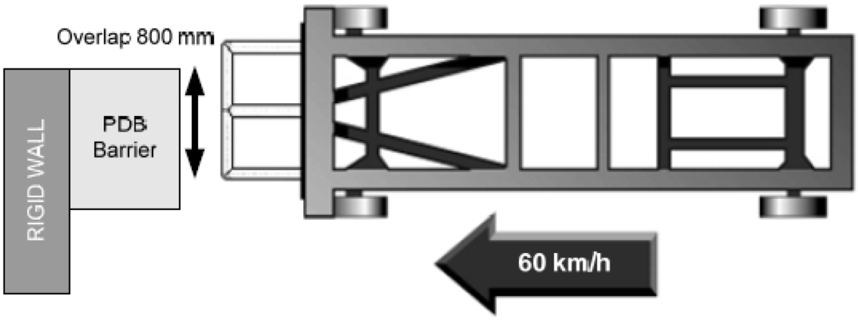


Figure C-10: Test set-up tube impactor.

Figure C-11: trolley with tube impactor.

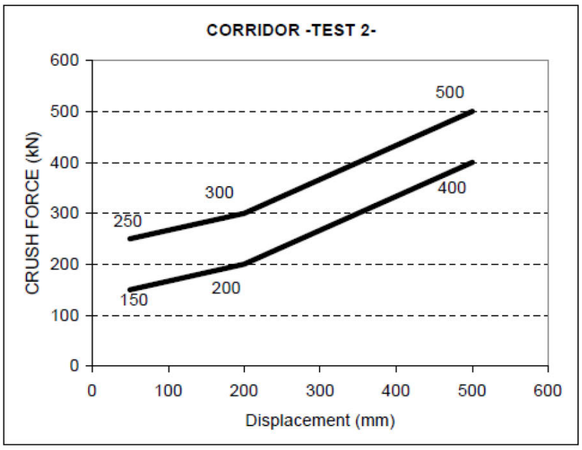


Figure C-12: Corridor tube impactor test.

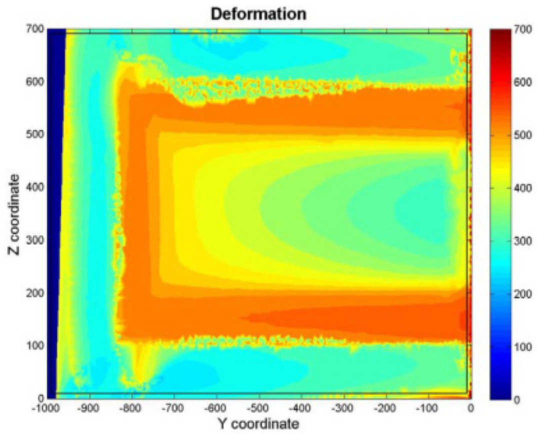


Figure C-13: barrier deformation tube impactor test.

ANNEX D: PDB SCAN PROCEDURE

The PDB deformed face digitization is a protocol based on 3D scanner facility to create a numeric picture of the deformed PDB face. The result of the digitization is a file with a specific format, allowing mathematical treatment with a specific barrier deformation analysis software.

EXAMPLE OF FACILITY

The facilities needed are composed of a 3D scanner, useable with a 3D arm facility.

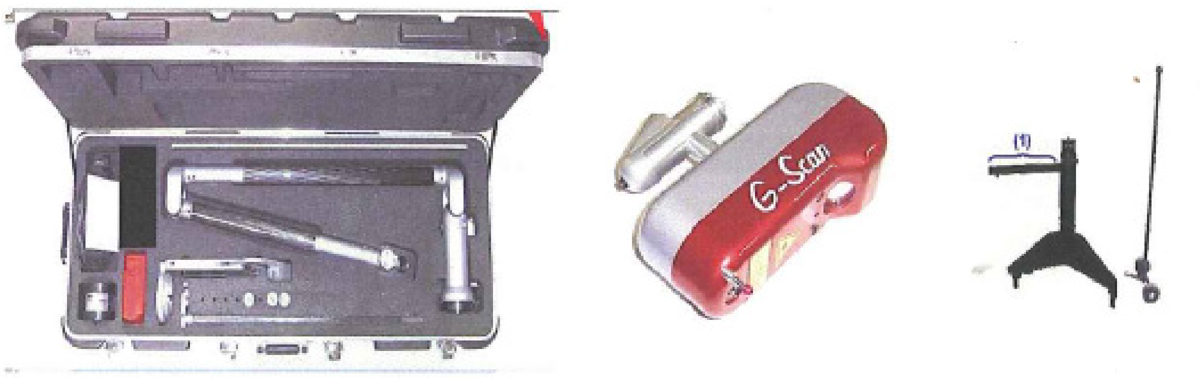


Figure D-1: Example of a 3D arm and 3D scanner.

POSITION OF BARRIER REFERENCE POINT

First, the digitization of the barrier is done by positioning the barrier on a reference surface, which it will remain exactly the same position throughout all the digitization. The barrier has to be temporary fixed or attached to the support. In Figure D-2, you can see an example to fix the barrier on rigid support. This reference position must be the same as the reference position taken to make an assessment on a car.

The ground must be as flat as possible and the fixation points must restrain the barrier to avoid any movements.

Figure D-2: PDB barrier positioning and fixation.

The reference point used as the origin is the lower, rear, corner opposite to the crash side. This corner has not been impacted during the crash, so there is no deformation of the honeycomb.

Frame origin

Figure D-3: Origin of the PDB

According to different front ends structures of vehicles to be tested, and reactions that occurs on PDB deformed face, the reference frame can be determined in two different cases due to the deformation of PDB back plate during the crash are seen in Figures D-4 and D-5:

- <u>Back plate reference</u> (intersections of green lines in Figure D-4&D-5) is not deformed. That occurs when honeycomb is still stuck to the back plate without space between both components. In that case, the origin frame must be taken from the back plate as close as possible from the honeycomb corner.

- <u>honeycomb reference</u> (intersection of red lines in Figure D-4&D-5). Occurs when interactions between vehicle and barrier make deformation on the back plate during the crash. This situation is often similar to a hole created on the deformed face PDB. In that case, the frame origin must be taken at the bottom corner of the honeycomb.

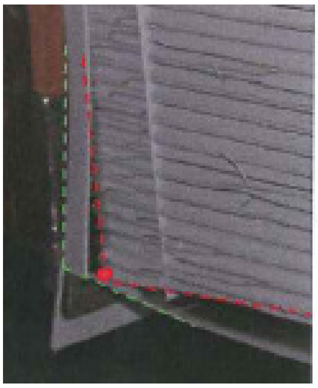


Figure D-4: Origin of PDB in cases the honeycomb seperates from the back plate

With the 3D tools, this origin frame must be determined by the intersection of the 3 straight lines of the honeycomb (see Figure D-5).

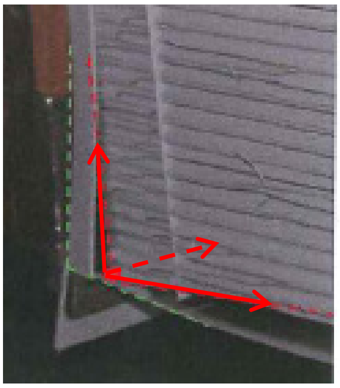


Figure D-5: Coordinate system of PDB in cases the honeycomb seperates from the back plate

SURFACES TO BE SCANNED

Main issues of PDB barrier analysis comes from the deformed front surface. Therefore the digitization must concern the front surface increased by 50 mm on all sides. In Figure D-6, the surface delimited by the red line plus 50 mm on the 4 sides is shown. The extra area is needed to be sure to catch all the involved front surface.

To be able to have the exact position of the front deformed surfaced of the deformed PDB, it is important to digitize the line from the origin frame to the deformed surface.

Result of the digitization is representing on Figure D-7.

Figure D-6: Front surface + 50 mm digitization area

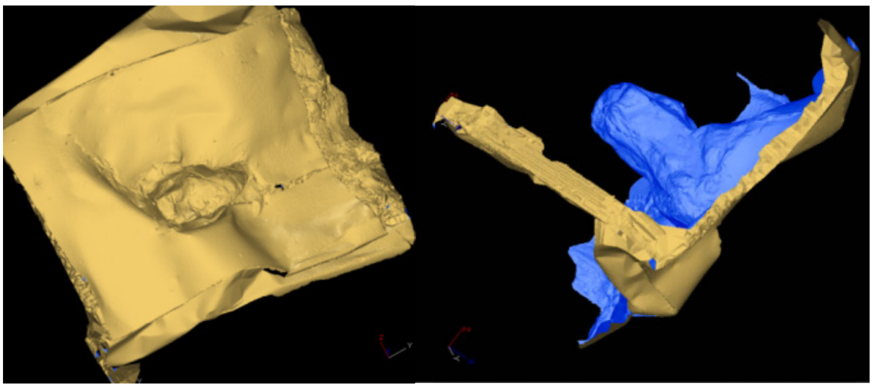


Figure D-7: digitize surface representation need to be performed.

The digitization of the front deformed PDB face is done with the scanner, following the same principle as painting an element with spray print. The quality of q deformed PDB's digitization comes from surface finish of deformed face and number of numeric points recorded.

Covering the aluminium barrier face with a matte paint facilitates the measurement of points with the scanner. On the other hand, the number of numeric points recorded result from the way the 3D scanner passes over the surfaces being scanned.

To guide a user when digitizing objects correctly, the 3D scanner is equipped with "a good position visualisation". This is composed of one red line which shows users the surfaces scanned, and a reference point as seen in Figure D-8.

Figure D-8: Positioning visualisation.

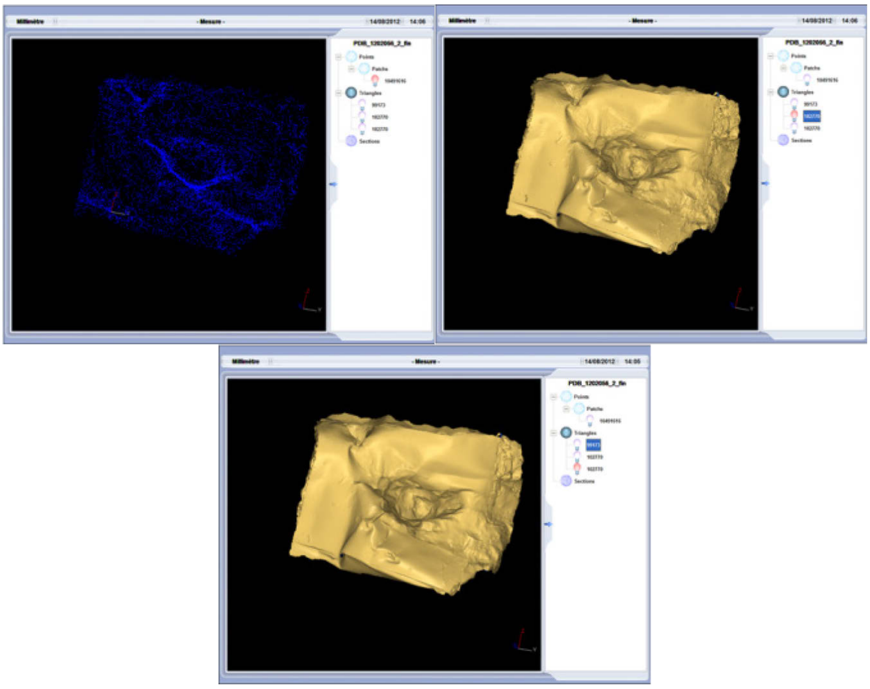
The digitization of the deformed PDB face consists in passing the scanner over all the front surface of the barrier. By crossing the various passages of the scan, it helps to have better quality digitization, according to the same principle of spray paint (Figure D-9)

Figure D-9: Scanning of all front surface areas.

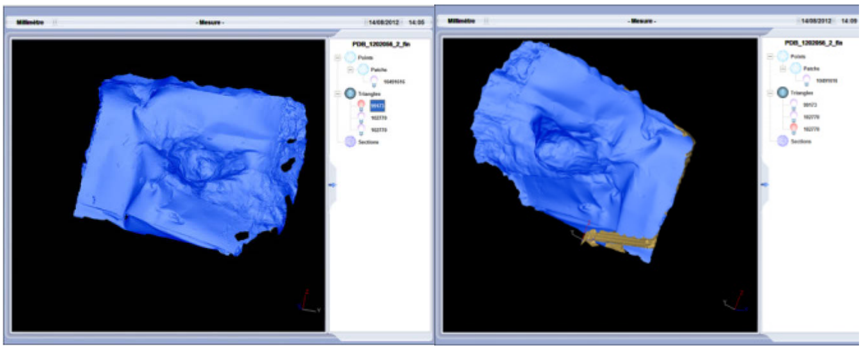
In some case, parts of a barrier are unreachable with the 3D scanner, especially when the deformed barrier has a hole. Depending to the size of this hole, the scanner may not be introduced in hole. In this situation it is necessary to scan a maximum surface with the 3D scanner equipped with a punctual sensor, identify missing points and record them by points clouds (Figure D-10).

Figure D-10: Manual digitation of points that cannot be scanned

3D scanner software is able to make triangular meshes of clouds points (Figure D-11) according to the precision settings. Depending on the precision, the deformed face of PDB barrier is more or less smooth.



PDB digitation from front view



PDB digitalisation from rear view

Figure D-11: PDB digitation from different views.

Deformed PDB face digitization is complete when the digitalization is able to represent the deformed face, with any holes, as few points as possible. Optimum digitization is a representation with no hole. Global representation of the result is available on Figure D-7.

GENERAL REMARKS

The number of required elements is estimated to be around 80 000 elements to have a good representation for the graphic representation, with main unit to respect

- Unit: mm,
- Means dimensions of elements close to 5mm,
- The coordinated of nodes are included in the following intervals in each axis:

For a left hand drive car

X: 0 ➔ 790mm
Y: 0 ➔ 1000mm
Z: 0 ➔ 700mm

For a right hand drive car

X: 0 → 790mm
Y: -1000 → 0mm
Z: 0 → 700mm

RULE

- the digitization must be performed without any intervention on the deformed face. All the deformations made on the barrier by the vehicle onto the barrier must be scanned. This rule is true before and also after digitizing the barrier.

DATA FILES STANDARD

Example of STL File format

Starting of stl file:

Solid

Face normal -0.944588 -0.299744 0.133817

Outer loop

Vertex 699.199493 44.990338 464.111826

Vertex 699.400769 40.254919 454.925475

Vertex 704.398190 28.842159 464.637274

Endloop

endfacet

Face normal -0.951527 -0.306960 -0.019296

Outer loop

Vertex 699.199493 44.990338 464.111826

Vertex 704.398190 28.842159 464.637274

Vertex 702.288054 34.774403 474.322900

Endloop

endfacet

Face normal -0.340816 -0.858930 0.382210

Outer loop

Vertex 693.491814 48.491214 440.798902

Vertex 684.318998 53.859586 444.683700

.

.

.

End of stl file

ANNEX E: TEST REPORTS

Supermini 1 PDB 60 km/h @ UTAC

Supermini 2 PDB 60 km/h @ FIAT

Supermini 2 PDB 60 km/h @ BASt test 1

Supermini 2 PDB 60 km/h @ BASt test 1

Supermini 2 PDB 60 km/h @ BASt test 2

City Car 1 PDB 60 km/h @ UTAC

Small Family Car 1 PDB 60 km/h @ IDIADA

SUV 1 PDB 60 km/h @ IDIADA

9 SUPERMINI 1 PDB 60 KM/H @ UTAC

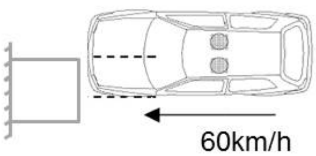
Offset Test
Supermini 1

AFFSEP1102784

Analysis and Report

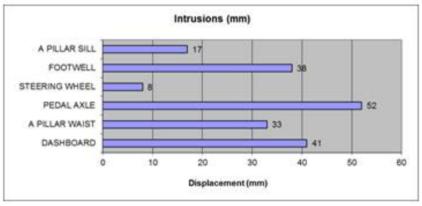
PDB Supermini 1

Test Date:	09, 2011
Location:	UTAC
Topic:	PDB-Test
Mass Ratio:	N/A
Test Number:	AFFSEP1102784
Test Protocol:	N/A

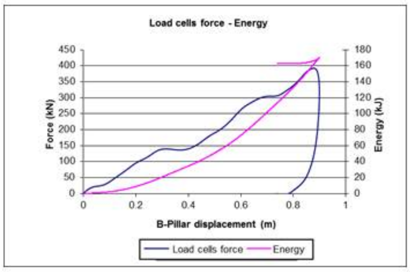


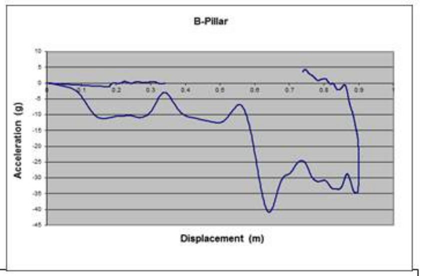
Vehicle 1:	Super Mini	Barrier: PDB v8
Brand/type:	Supermini 1	
Engine	1.4L, 4 cylinders	
Impact side:	Front left	
Speed:	60,48 km/h	
Overlap:	50 %	
Test mass:	1345 kg	
Dummy:	LHS – HIII 50% RHS – HIII 50%	

2- SELF PROTECTION : Structural analysis (1/2)



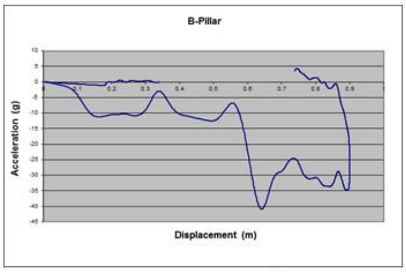
Average intrusion	
36,2 mm up = 37mm low=35,7mm	
Maximum force	
392 kN	
EES	
48,7 km/h	

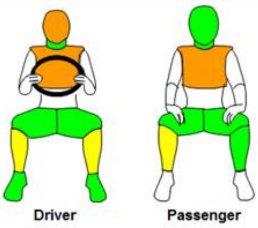




⇨ Medium compartment intrusion

2- SELF PROTECTION : Dummies (2/2)



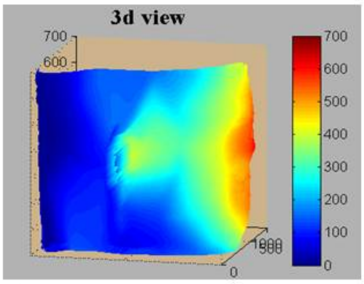


* Rating representation

		DRIVER	PASS	ECE R94
Head	HIC	502	338	<1000
	Criteria 3ms (g)	82,2	49,1	<80g
Upper Neck	NIC	<corridor		<corridor
	My (Nm)	24,8	27,2	<57 Nm
Chest	Deflexion (mm)	39,7	32,5	<50mm
	Viscous criterion	0,19	0,18	<1 m/s
Femur	Force	<corridor		<corridor
Knee	Left disp, (mm)	0,59	0,14	<15mm
	Right disp, (mm)	0,02	0,12	<15mm
Tibia Index	Left upper	0,54	0,33	<1,3
	Left lower	0,32	0,20	<1,3
	Right upper	0,44	0,41	<1,3
	Right lower	0,25	0,21	<1,3

Dummies criteria far from R94 limits

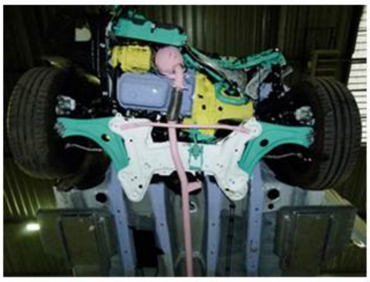
3- PARTNER PROTECTION ANALYSIS: PDB (1/2)



MAX DEFORMATION	VOLUME	ENERGY
405 mm	139 dm3	63,9 kJ

* Calculated with current formula

3- PARTNER PROTECTION ANALYSIS: Front end (2/2)

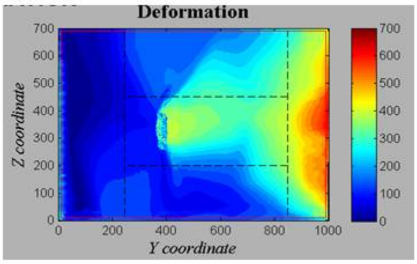


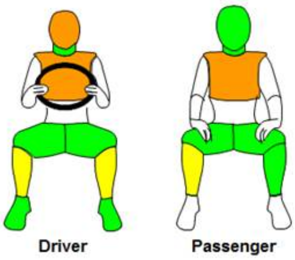
4- PARTNER AND SELF PROTECTION ASSESSMENTS

SELF

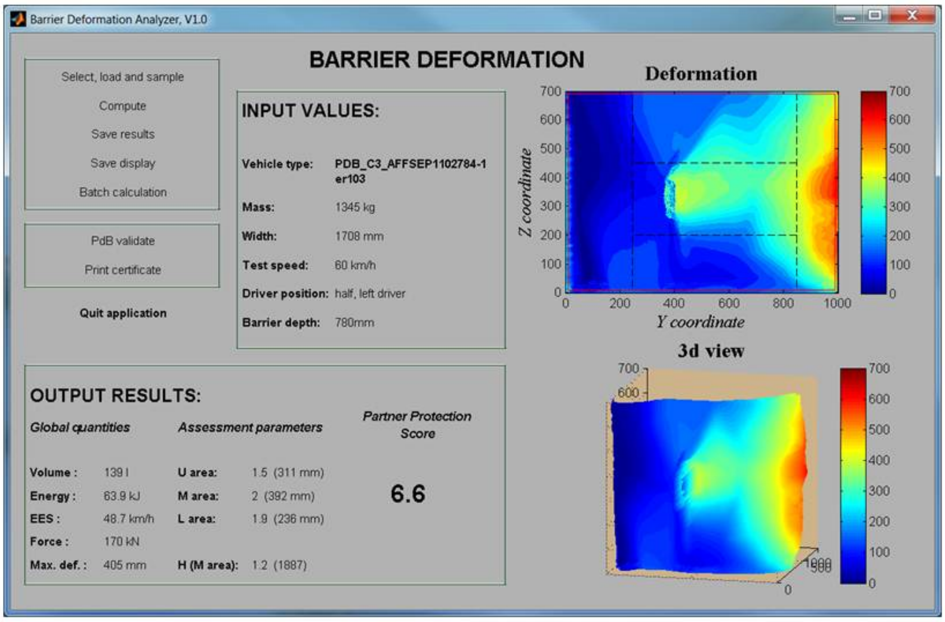
PARTNER

Graphe intrusion





4- BACK UP



10 SUPERMINI 2 PDB 60 KM/H @ FIAT

Offset Test
Supermini 1 2; PDB

Analysis and Report

Stefano Candellero (FIAT)

FIMCAR WP 2, 14th February 2012

Test comparison (test set-up´s)

PDB (60 kph)
Supermini 2: 1.2 Bz, LHD, POP
Barrier: PDB AFL v8.0 XT
Test weight: 1160 kg
Velocity: 60 kph

M-PDB (50 kph)
Supermini 2 : 1.2 Bz, LHD, POP
Trolley: TNO, v8.0 PDB
Test weight: 1160 kg (500), 1514 kg (Trolley)
Velocity: 50 kph (100 kph closing speed)

M-PDB (56 kph)
Supermini 2 : 1.2 Bz, LHD, POP
Trolley: TNO, v8.0 PDB
Test weight: 1225 kg (500), 1487 kg (Trolley)
Velocity: 56 kph (112 kph closing speed)

Eu-NCAP
Supermini 2 : 1.2 Bz, LHD, POP
Test weight: 1191 kg
Velocity: 64 kph

ECE94
Supermini 2 : 1.3 JTD, LHD *
Test weight: 1321 kg
Velocity: 56 kph

* ECE94 test was perfomed with a different engine and different restraint system

2

Biomechanical results in EuNcap rating form

SUMMARY	PDB 60 kph Driver	PDB 60 kph Passenger	MPDB 50 kph Driver	MPDB 50 kph Passenger
Head and Neck assessment	4.000	4.000	4.000	4.000
Chest assessment	3.129	2.957	2.429	3.757
Knee, Femur and Pelvis assessment	2.729	4.000	1.236	4.000
Lower Leg, Foot and Ankle Assessment	2.800	3.289	1.822	1.333
TOTAL	12.658	14.246	9.487	13.090
TOTAL FRONTAL	12.486		8.998	

SUMMARY	MPDB 56 kph Driver	MPDB 56 kph Passenger	EuNCAP Driver	EuNCAP Passenger
Head and Neck assessment	0.000	4.000	4.000	4.000
Chest assessment	1.771	0.729	3.820	3.940
Knee, Femur and Pelvis assessment	4.000	4.000	4.000	4.000
Lower Leg, Foot and Ankle Assessment	1.911	2.222	3.290	3.840
TOTAL	7.682	10.951	15.110	15.780
TOTAL FRONTAL	6.640*		15.110	

*: 0 points with test capping

ECE94 biomechanical results not comparable because the test was performed with a different restraint system (fitted on a version with a very low volume of sales – without kneebag)

Test	Compliance to ECE r94
PDB 60 kph	Compliant
MPDB 50 kph	Compliant
MPDB 56 kph	Not compliant (Head)
EuNCAP	Compliant

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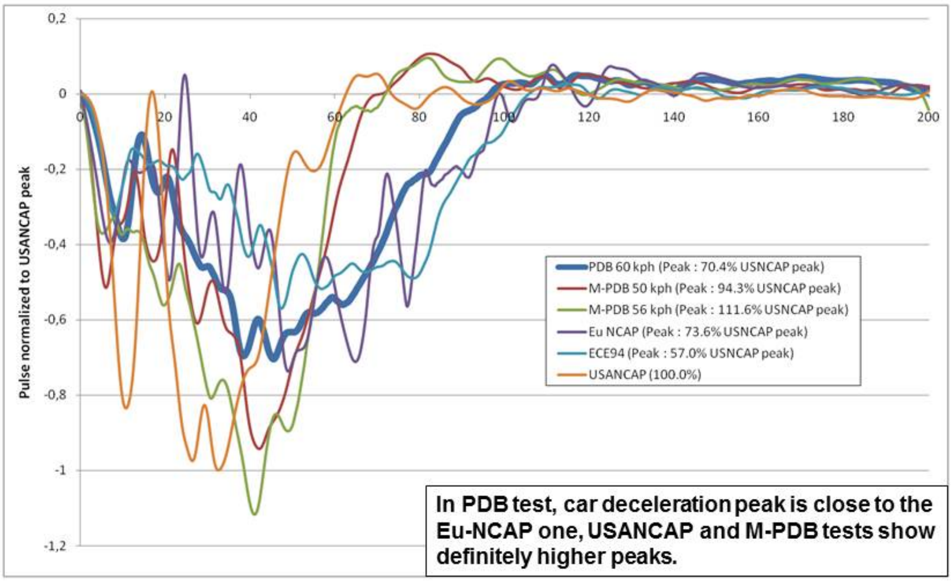
Normalized pulses



In PDB test, car deceleration peak is close to the Eu-NCAP one, USANCAP and M-PDB tests show definitely higher peaks.

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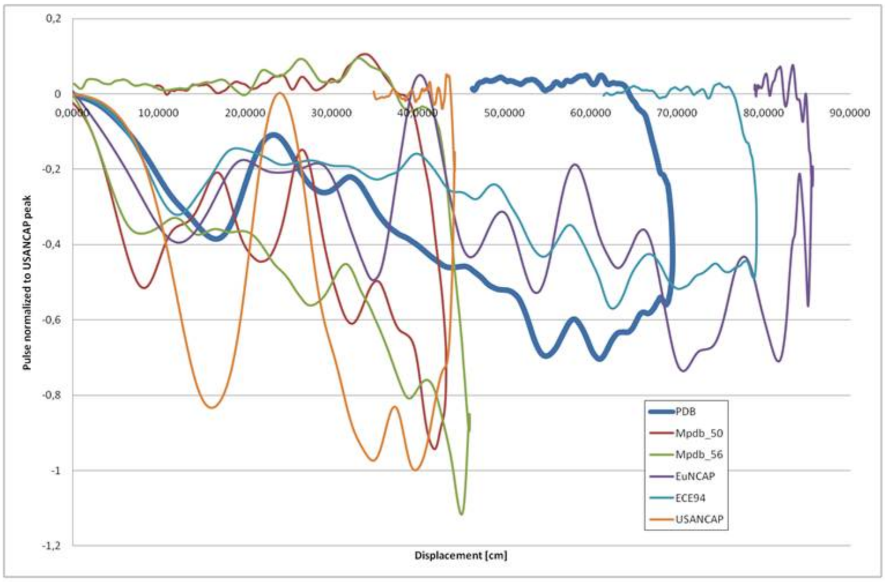
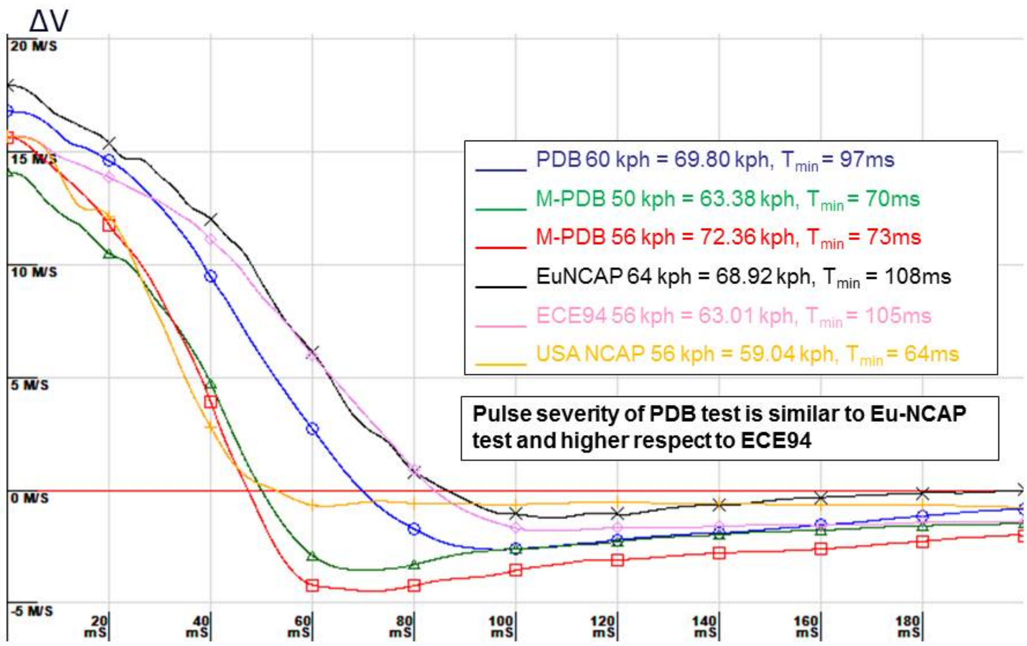
Pulse Vs. absolute car displacement





Static measurements

Frontal Impact	Rearw. Steering wheel displacment	Rearw. A pillar displacement	Rearward pedal fixation displacement	Rearw. Pedals displacement	Upward. Pedals displacement
Remarks	(mm)	(mm)	(mm)	(mm)	(mm)
PDB 60 kph	-11	1	47	-3 (accel)	-19 (accel)
M-PDB 50 kph	9	22	103	19 (accel)	-27 (brake)
M-PDB 56 kph	31	71	---	14 (clutch)	37 (clutch)
EuNCAP 64 kph	-4	7	68	1 (accel)	-21 (accel)
ECE94 56 kph	-13	1	37	-5 (accel)	-32 (accel)

PDB's level of intrusion is low and close to ECE94.

Barrier deformations (1/3)

PDB 60kph

Evident rupture in PDB barrier (similar to EEVC barrier in front Eu-NCAP test), instability is dangerous when using barrier scanning for rating (or others evaluations).

Barrier deformations (2/3)

MPDB 50 kph

Barrier static measurements expected from TNO

MPDB 56 kph

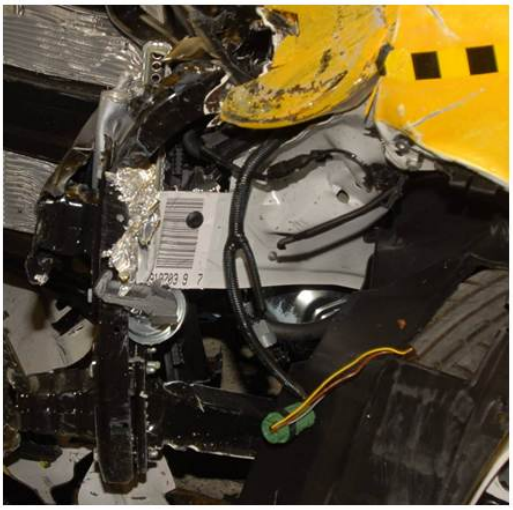
Barrier deformations (3/3)

EuNCAP

ECE94

Bumper-beam and longitudinals deformations (1/2)

PDB 60 kph



Bumper-beam and longitudinals deformations (2/2)

MPDB
50 kph

MPDB
56 kph

Longitudinals and third load path deformations

M-PDB 50kph

M-PDB 56kph

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Longitudinals (PDB 60kph Vs. Eu-NCAP)

PDB 60kph

Eu-NCAP

PDB barrier stress less the longitudinals respect to EEVC barrier in Eu-NCAP test (loads on longitudinals aren't sufficient for longitudinal collapse).

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PDB 'Supermini 2'

Test Date:	12/04/2012
Location:	BASt
Topic:	PDB-Test
Mass Ratio:	N/A
Test Number:	**FM03OPDB**
Test Protocol:	ECE R-94 with amend. ECE/TRANS /WP.29/GRSP/2007/17e

Vehicle:	Supermini 2	Barrier:	PDB - AFL
Type:			Prod101XT Version V8.0
			Ser. No.: CP809413
Impact side:	Front		
Speed:	60,08 km/h	Impact accuracy:	87mm left (more overlap)
Offset:	50 %		7 mm lower
Test mass:	1164 kg	LCW/barrier	153 mm left
Dummy:	LHS – Hybrid III 50th	ground clearance:	149 mm right
	RHS – Hybrid III 50th	Barrier dimensions:	1000 mm wide
			700 mm high
			790 mm long

Test objectives:
Test to check reproducibility of PDB testing procedure (to be compared to PDB-Test 17292 conducted at Fiat and PDB-Test FM02OPDB at BASt)

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Test parameters

Vehicle data:

- **Vehicle: Supermini 2, *model year: 07/2010* (LHD)**
- **Vehicle identification no (VIN):**
- **Engine / Transmission: 1.2 l petrol / manual**
- **Test speed: 60.08 km/h**
- **Test weight: 1164 kg (FL/FR 343 / 327) (RL/RR 245 /249)**
- **Test impact accuracy:**
  lateral 87mm left (more overlap) and vertical 7 mm lower

Test vehicle status:

- **Safety systems: 3 point belt system with pretensioner (retractor & buckle) and load limiter, dual stage airbag driver/passenger, knee airbag driver, side and window airbag**
- **Wheels: steel, 175/65 R14, 2.2 bar**
- ***Ride height measurements:***
  FL: 634 mm, FR: 633 mm
  RL: 618 mm, RR: 620 mm

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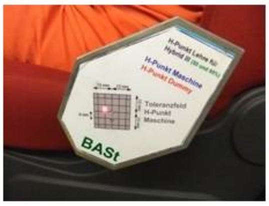
Pre-test Pictures
Vehicle

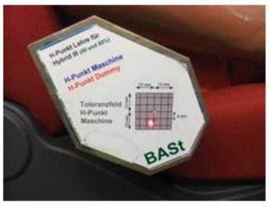
Pre-test Pictures
Barrier

Additional Pre-test pictures

H-Point Driver



H-Point Passenger



Description of front-end structure

Three front load paths

- *Upper load path: Frontend assembly/radiator support at bonnet leading edge*
- *Lower load path: Longitudinals / crush can/ bumper crossbeam → PEAS*
- *3rd load path: Sub frame/crush can/crossbeam → SEAS*
- *Vertical connection between all load paths*

Dimensions [mm] (heights above ground)	Top height	Bottom height	Width	Depth
Engine	737	167	470	263
Gear Box	370	160	372	-
Higher Crossbeam	661	539	-	-
Lower Crossbeam	350	300	-	-
Subframe	-	210	560	-

Vehicle / barrier results

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Post-test Pictures
Vehicle

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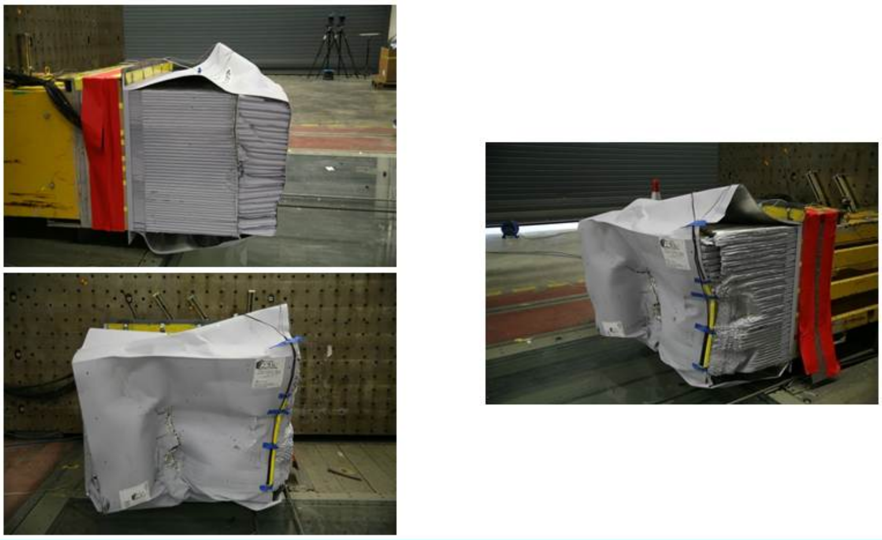
Post-test Pictures
Front End Structure

Post-test Pictures
Barrier



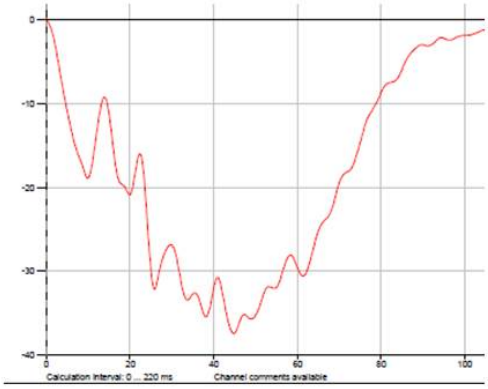
Additional Post-test pictures

Static deformation in x-direction

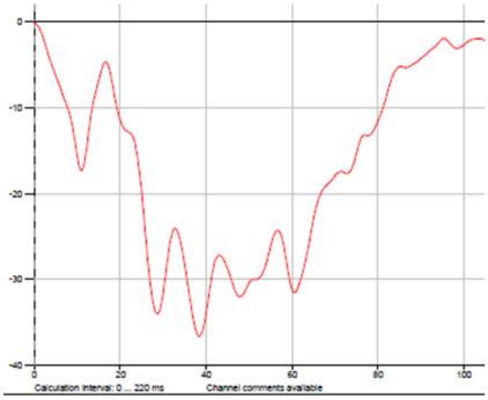
Location	Difference x	y	z
A-post-RHS-waist	0,51	5,72	3,82
A-post-RHS-sill	1,44	4,77	2,26
B-post-RHS-waist	1,23	0,54	0,57
B-post-RHS-sill	0,17	0,69	0,46
A-post-LHS-waist	2,76	2,22	0,76
A-post-LHS-sill	0,74	1,69	0,30
B-post-LHS-waist	0,12	2,35	2,40
B-post-LHS-sill	0,60	2,04	2,05
Centre of the accelerator pedal	5,99	37,57	21,24
Centre of the brake pedal	27,46	2,33	12,16
Centre of the clutch pedal	88,10	7,05	30,39
Centre of the steering column	14,57	0,84	11,96

Vehicle Accelerations in X

A-Pillar lower left

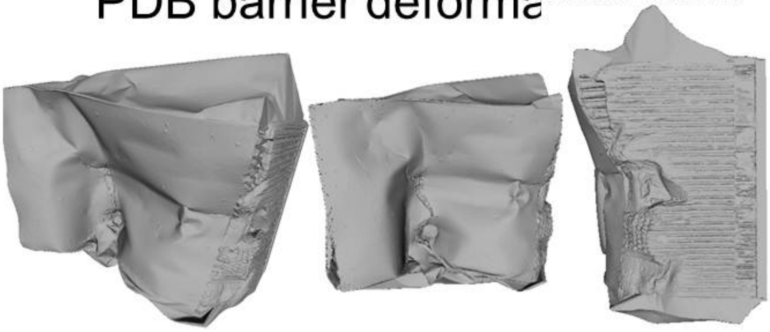


A-Pillar lower right



PDB barrier deformation results

PDB barrier deformation scan



scans available in three resolution:

- high (1 mm)
- mid (2 mm)
- low (5 mm)

Dummy results

Dummy criteria Comparison

Supermini 2 PDB-Test 60km/h FM03OPDB

M03OPDB M03OPDB 012-04-12	Supermini 2 Type of Test Regulation	vs. PDB 50 Offset Frontal Impact Euro NCAP

Criterion	Driver SP 1 (H3)				Co-Driver SP 3 (H3)			
Head & Neck			4.000	★			4.000	★
Head								
HIC 36	934.16				355.22			
Acceleration Resultant	72.00	g	4.000	★	45.64	g	4.000	★
3ms cumulative	70.30	g			44.83	g		
Neck								
Shear Force Fx+	0.91	kN	4.000	★	0.43	kN	4.000	★
Shear Force Fx-	-0.38	kN	4.000	★	-0.30	kN	4.000	★
Tensile Force Fz+	1.86	kN	4.000	★	1.26	kN	4.000	★
Extension My-	-16.76	Nm	4.000	★	-16.16	Nm	4.000	★
Chest			1.966	★			2.947	★
Deflection	-36.24	mm	1.966	★	-29.37	mm	2.947	★
VC max	0.23	m/s	4.000	★	0.19	m/s	4.000	★
belt at upper diagonal belt Force	4.19	kN			3.97	kN		

FM02OPDB FM02OPDB 2012-01-26	Supermini 2 Type of Test Regulation	vs. PDB 50 Offset Frontal Impact Euro NCAP

Criterion	Driver SP 1 (H3)				Co-Driver SP 3 (H3)			
Femur & Knee			2.875	★			4.000	★
Left								
Femur Force Fz-	-0.66	kN	4.000	★	-0.53	kN	4.000	★
Knee Slider Displacement	-0.97	mm	4.000	★	-0.06	mm	4.000	★
Right								
Femur Force Fz-	-2.46	kN	4.000	★	-0.47	kN	4.000	★
Knee Slider Displacement	-8.53	mm	2.875	★	-0.18	mm	4.000	★
Tibia			3.091	★			2.540	★
Left								
Compression Upper Fz-	-1.26	kN	4.000	★	-2.51	kN	3.658	★
Compression Lower Fz-	-1.45	kN	4.000	★	-3.47	kN	3.023	★
Tibia Index Upper	0.46		3.745	★	0.73		2.540	★
Tibia Index Lower	0.24		4.000	★	0.44		3.819	★
Right								
Compression Upper Fz-	-1.91	kN	4.000	★	-1.62	kN	4.000	★
Compression Lower Fz-	-2.04	kN	3.975	★	-2.00	kN	4.000	★
Tibia Index Upper	0.60		3.091	★	0.51		3.510	★
Tibia Index Lower	0.25		4.000	★	0.43		3.875	★
Sum			11.932				13.487	

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Dummy criteria Comparison

PDB-Test 60km/h

Body Region	SP 1		SP 3	
Head & Neck	4.000	★	4.000	★
Chest	1.966	★	2.947	★
Femur & Knee	2.875	★	4.000	★
Tibia	3.091	★	2.540	★
Sum	11.932		13.487	

EuroNCAP ODB-Test 64 km/h

SUMMARY

Supermini 2

Adult Occupant Rating

★★★★★

Frontal Driver	
Head and Neck assessment	4.00
Chest assessment	3.82
Knee, Femur and Pelvis assessment	4.00
Lower Leg, Foot and Ankle assessme	3.29
Frontal Passenger	
Head and Neck assessment	4.00
Chest assessment	3.94
Knee, Femur and Pelvis assessment	4.00
Lower Leg assessment	3.84
Door Opening	0
OVERALL FRONT	15.11

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Firing times

- Driver Airbag:
  Stage 1 at 18,9 ms
  Stage 2 at 22,5 ms

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fron tal impact and co mpatibility assessment research

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11 SUPERMINI 2 PDB 60 KM/H @ BAST TEST 1

Offset Test
Supermini 2

FM02OPDB

Analysis and Report

Holger Schwedhelm,
Thorsten Adolph

FIMCAR WP 2, 30th May 2012

SEVENTH FRAMEWORK PROGRAMME

PDB 'Supermini 2'

Test Date:	26/01/2012
Location:	BASt
Topic:	PDB-Test
Mass Ratio:	N/A
Test Number:	**FM02OPDB**
Test Protocol:	ECE R-94 with amend. ECE/TRANS /WP.29/GRSP/2007/17e

Vehicle:	Supermini 2	Barrier:	PDB - AFL
Type:	(silver)		Prod101XT Version V8.0
Impact side:	Front		Ser. No.: CP0809401
Speed:	60,01 km/h	Impact accuracy:	35 mm left (more overlap)
Offset:	50 %		12 mm up
Test mass:	1165 kg	LCW/barrier	152 mm left
Dummy:	LHS – Hybrid III 50th	ground clearance:	151 mm right
	RHS – Hybrid III 50th	Barrier dimensions:	1000 mm wide
			700 mm high
			790 mm long

Test objectives:
Test to check reproducibility of PDB testing procedure (to be compared to PDB-Test 17292 conducted at Fiat)

SEVENTH FRAMEWORK PROGRAMME

Test parameters

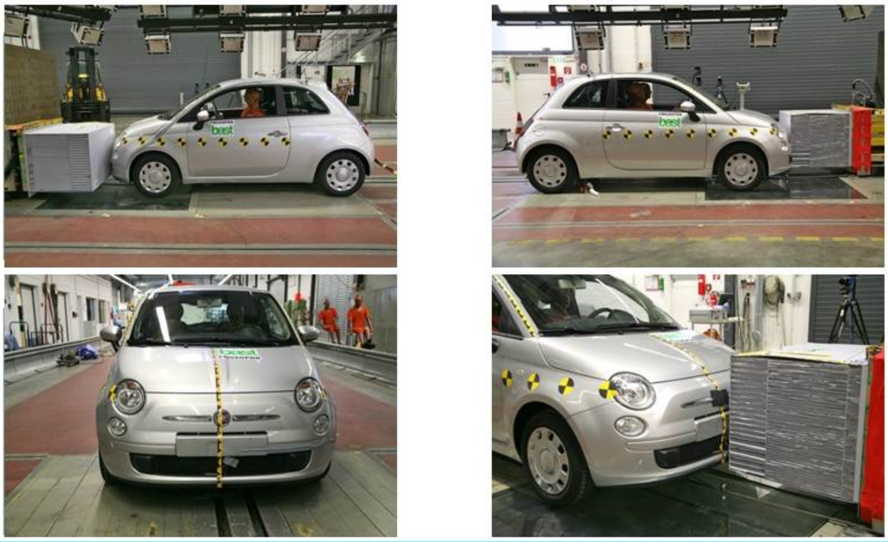
Vehicle data:

- Vehicle: Supermini 2, *model year: 05/2010* (LHD)
- Vehicle identification no (VIN):
- Engine / Transmission: 1.2 l petrol / manual
- Test speed: 60.01 km/h
- Test weight: F: 680 kg / R: 485 kg Total: 1165 kg
- Test impact accuracy:
  lateral 35 mm left (more overlap) and vertical 12 mm up

Test vehicle status:

- Safety systems: 3 point belt system with pretensioner (retractor & buckle) and load limiter, dual stage airbag driver/passenger, knee airbag driver, side and window airbag → airbag control unit did not fire
- Wheels: steel, 175/65 R14, 2.2 bar
- *Ride height measurements:*
  FL: 622 mm, FR: 619 mm
  RL: 614 mm, RR: 615 mm

Pre-test Pictures
Vehicle



Pre-test Pictures
Barrier

Additional Pre-test pictures

H-Point Driver

H-Point Passenger

Description of front-end structure

Three front load paths

- *Upper load path: Frontend assembly/radiator support at bonnet leading edge*
- *Lower load path: Longitudinals / crush can/ bumper crossbeam → PEAS*
- *3rd load path: Sub frame/crush can/crossbeam → SEAS*
- *Vertical connection between all load paths*

Dimensions [mm] (heights above ground)	Top height	Bottom height	Width	Depth
Engine	737	167	470	263
Gear Box	370	160	372	-
Higher Crossbeam	661	539	-	-
Lower Crossbeam	350	300	-	-
Subframe	-	210	560	-

Vehicle / barrier results

Post-test Pictures
Vehicle

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SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Front End Structure

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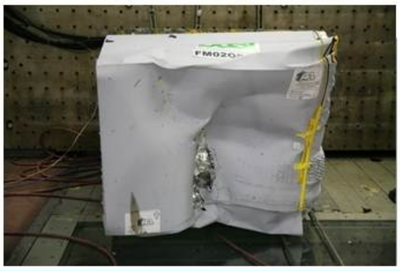
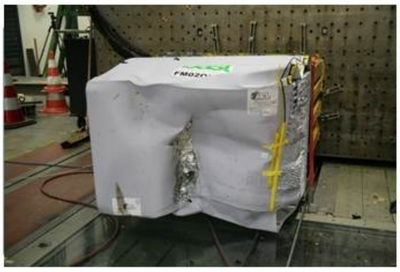
SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Barrier





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Additional Post-test pictures

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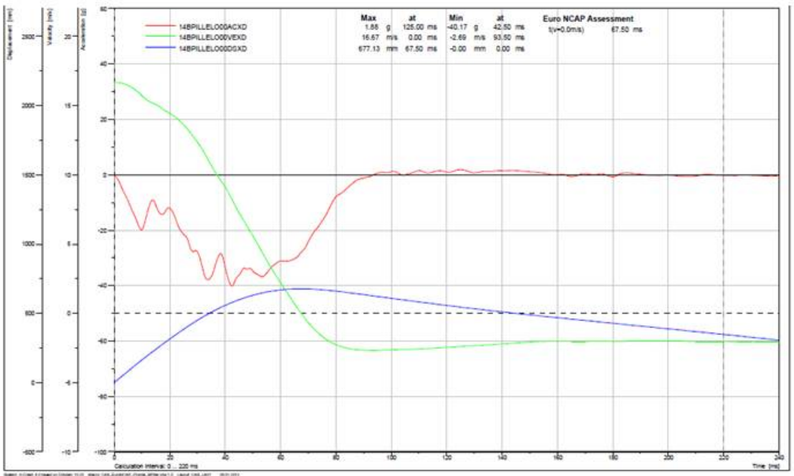
Static deformation in x-direction

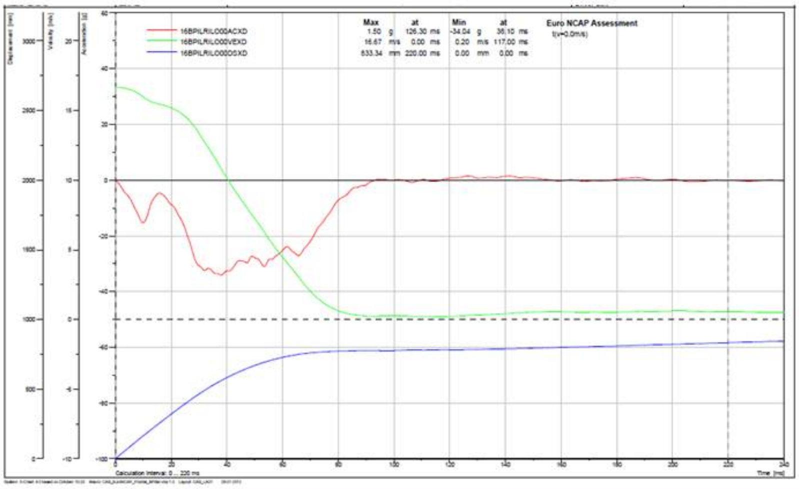
Location		Difference
A-pillar-waist	x	1,0
	y	3,1
	z	1,3
A-pillar-sill	x	0,1
	y	1,7
	z	1,9
B-pillar-waist	x	0,4
	y	0,1
	z	0,6
B-pillar-sill	x	0,3
	y	0,7
	z	0,7

Vehicle Accelerations/Velocities/Displacements B-Pillar Left Lower X



Vehicle Accelerations/Velocities/Displacements

B-Pillar right Lower X



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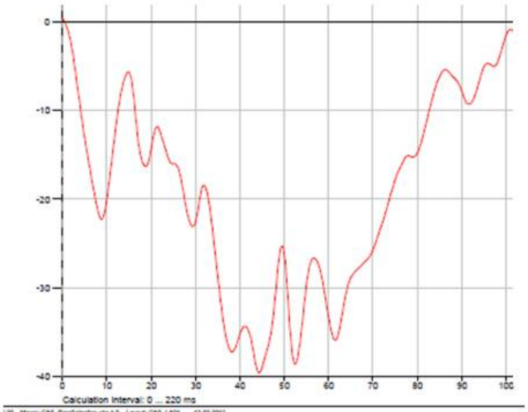
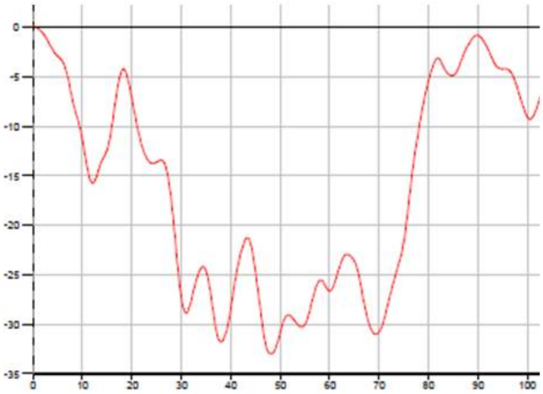
Vehicle Accelerations

A-Pillar middle left



A-Pillar middle right



FIMCAR frontal impact and compatibility assessment research

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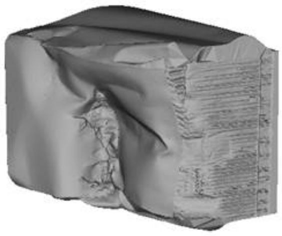
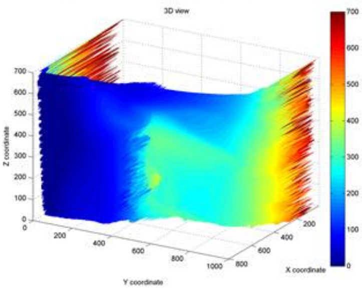
PDB barrier deformation results

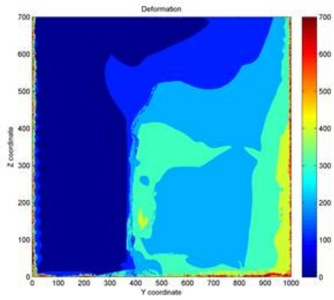
PDB barrier deformation scan



scans available in three resolution:

- high (1 mm)
- mid (2 mm)
- low (5 mm)

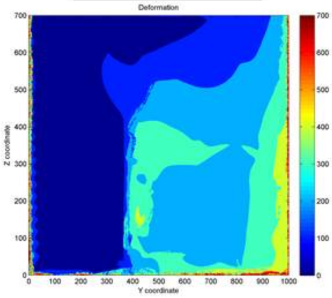


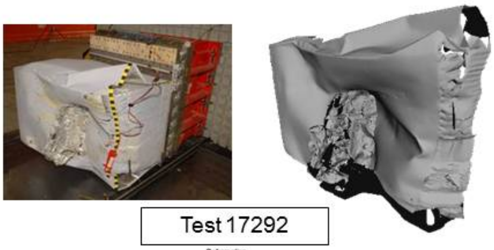


high resolution

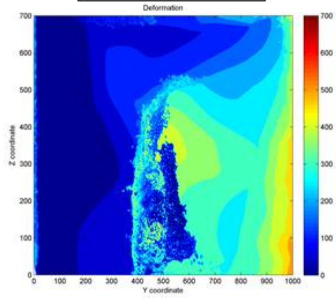
Comparison with test 17292

Test FM02OPDB





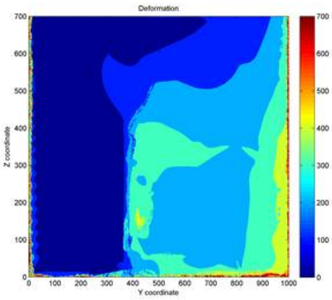
Test 17292



Metric evaluation/R&R

Test FM02OPDB

high resolution

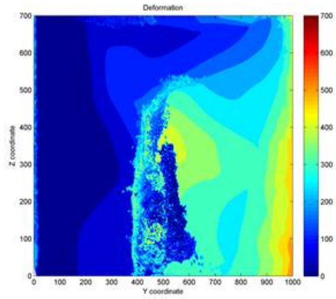


SDI (smooth deformation index):

Low resolution: 209,572
Mid resolution: 209,508
High resolution: 209,418

hardly any difference using different resolutions

Test 17292



SDI
(smooth deformation index):

122,006 → scanning procedure and post-processing of stl-file needs to be checked

Dummy results

Dummy criteria Comparison

Supermini 2 PDB-Test 60km/h FM02OPDB

FM02OPDB
FM02OPDB
2012-01-26
Supermini 2 vs. PDB 50 Offset
Type of Test: Frontal Impact
Regulation: Euro NCAP

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (H3)		
Head & Neck			0.000			0.000
Head						
HIC 36	2858.76		0.000	1863.88		0.000
Acceleration Resultant	169.61	g		247.68	g	
3ms cumulative	158.61	g	0.000	129.30	g	0.000
Neck						
Shear Force Fx+	0.40	kN	4.000	0.59	kN	4.000
Shear Force Fx-	-1.85	kN	4.000	-0.99	kN	4.000
Tensile Force Fz+	5.73	kN	0.000	2.79	kN	3.390
Extension My-	-74.56	Nm	0.000	-31.20	Nm	4.000
Chest			1.749			3.217
Deflection	-37.76	mm	1.749	-27.48	mm	3.217
VC max	0.30	m/s	4.000	0.13	m/s	4.000
belt at upper diagonal belt Force	3.91	kN		3.41	kN	

airbag control unit did not fire

FM02OPDB
FM02OPDB
2012-01-26
Supermini 2 vs. PDB 50 Offset
Type of Test: Frontal Impact
Regulation: Euro NCAP

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (H3)		
Femur & Knee			0.000			4.000
Left						
Femur Force Fz-	-3.41	kN	4.000	-0.64	kN	4.000
Knee Slider Displacement	-0.46	mm	4.000	-0.20	mm	4.000
Right						
Femur Force Fz-	-3.76	kN	4.000	-0.05	kN	4.000
Knee Slider Displacement	-17.20	mm	0.000	-0.09	mm	4.000
Tibia			0.415			2.483
Left						
Compression Upper Fz-	-2.74	kN	3.508	-2.19	kN	3.874
Compression Lower Fz-	-2.69	kN	3.538	-3.05	kN	3.298
Tibia Index Upper	0.50		3.545	0.61		3.087
Tibia Index Lower	0.40		4.000	0.29		4.000
Right						
Compression Upper Fz-	-1.67	kN	4.000	-2.27	kN	3.823
Compression Lower Fz-	-1.65	kN	4.000	-2.89	kN	3.409
Tibia Index Upper	1.21		0.415	0.74		2.483
Tibia Index Lower	0.29		4.000	0.43		3.882
Sum			0.000			0.000

Dummy criteria Comparison

PDB-Test 60km/h

FM02OPDB
FM02OPDB
2012-01-26

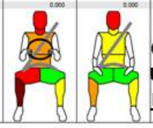
Fiat 500 vs. PDB 50 Offset
Frontal Impact
Euro NCAP

bast

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (H3)			Worst Points
Head & Neck			0.000			0.000	0.000
Head							
HIC 36	2858.76		0.000	1663.68		0.000	0.000
Acceleration Resultant	169.61	g		247.68	g		
3ms cumulative	158.61	g	0.000	129.30	g	0.000	0.000
Neck							
Shear Force Fx+	0.40	kN	4.000	0.59	kN	4.000	4.000
Shear Force Fx-	-1.85	kN	4.000	-0.99	kN	4.000	4.000
Tensile Force Fz+	6.73	kN	0.000	2.79	kN	3.390	0.000
Extension My-	-74.56	Nm	0.000	-31.20	Nm	4.000	0.000
Chest			1.749			3.217	1.749
Deflection	-37.76	mm	1.749	-27.48	mm	3.217	1.749
VC max	0.30	m/s	4.000	0.13	m/s	4.000	4.000
belt at upper diagonal belt Force	3.91	kN		3.41	kN		
Femur & Knee			0.000			4.000	0.000
Left							
Femur Force Fz-	-3.41	kN	4.000	-0.64	kN	4.000	4.000
Knee Slider Displacement	-0.46	mm	4.000	-0.20	mm	4.000	4.000
Right							
Femur Force Fz-	-3.76	kN	4.000	-0.05	kN	4.000	4.000
Knee Slider Displacement	-17.20	mm	0.000	-0.09	mm	4.000	0.000
Tibia			0.415			2.483	0.415
Left							
Compression Upper Fz-	-2.74	kN	3.508	-2.19	kN	3.874	3.508
Compression Lower Fz-	-2.69	kN	3.538	-3.05	kN	3.298	3.298
Tibia Index Upper	0.50		3.545	0.61		3.087	3.087
Tibia Index Lower	0.40		4.000	0.29		4.000	4.000
Right							
Compression Upper Fz-	-1.67	kN	4.000	-2.27	kN	3.823	3.823
Compression Lower Fz-	-1.86	kN	4.000	-2.89	kN	3.409	3.409
Tibia Index Upper	1.21		0.415	0.74		2.483	0.415
Tibia Index Lower	0.29		4.000	0.43		3.882	3.882
Sum			0.000			0.000	0.000

Rating without modifiers

Points
- 4.000
- 2.670 - 3.999
- 1.330 - 2.669
- 0.001 - 1.329
- 0.000



airbag control unit did not fire

Fiat 500
60.21 km/h
1160 kg
Driver Left

Load Cell Wall Fimcar
0.0 km/h
0 kg

Results Passengers
Front
Vehicle 1

Laboratory BASt
Customer Fimcar

EuroNCAP ODB-Test 64 km/h

SUMMARY

Supermini 2

Adult Occupant Rating

★★★★★

Frontal Driver	
Head and Neck assessment	4.00
Chest assessment	3.82
Knee, Femur and Pelvis assessment	4.00
Lower Leg, Foot and Ankle assessme	3.29
Frontal Passenger	
Head and Neck assessment	4.00
Chest assessment	3.94
Knee, Femur and Pelvis assessment	4.00
Lower Leg assessment	3.84
Door Opening	0
OVERALL FRONT	15.11

Firing times

- No firing times have been recorded
- The Airbag and the seat belt pretensioner have not been fired due to replacement of airbag control unit foreseen for 5 seater vehicle model

Conclusions

- In the test the seat belt pretensioner and the airbag have not fired due to a failure in the replacement of the control unit
- Acceleration: 40 g at b-pillar, left
- Dummy values: Extremely high acceleration of the head but considerably low chest compression for the passenger

12 SUPERMINI 2 PDB 60 KM/H @ BAST TEST 2

Offset Test
Supermini 2 vs PDB

FM03OPDB

Analysis and Report

Holger Schwedhelm,
Thorsten Adolph

FIMCAR WP 2, 1st June 2012

PDB 'Supermini 2'

Test Date:	12/04/2012
Location:	BASt
Topic:	PDB-Test
Mass Ratio:	N/A
Test Number:	**FM03OPDB**
Test Protocol:	ECE R-94 with amend. ECE/TRANS /WP.29/GRSP/2007/17e

Vehicle:	Supermini 2	Barrier:	PDB - AFL
Type:			Prod101XT Version V8.0
Impact side:	Front		Ser. No.: CP809413
Speed:	60,08 km/h	Impact accuracy:	87mm left (more overlap)
Offset:	50 %		7 mm lower
Test mass:	1164 kg	LCW/barrier	153 mm left
Dummy:	LHS – Hybrid III 50th	ground clearance:	149 mm right
	RHS – Hybrid III 50th	Barrier dimensions:	1000 mm wide
			700 mm high
			790 mm long

Test objectives:
Test to check reproducibility of PDB testing procedure (to be compared to PDB-Test 17292 conducted at Fiat and PDB-Test FM02OPDB at BASt)

Test parameters

Vehicle data:

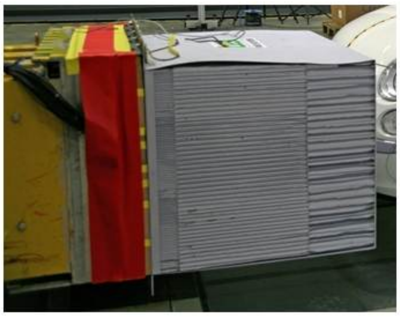
- Vehicle: Supermini 2, *model year: 07/2010* (LHD)
- Vehicle identification no (VIN):
- Engine / Transmission: 1.2 l petrol / manual
- Test speed: 60.08 km/h
- Test weight: 1164 kg (FL/FR 343 / 327) (RL/RR 245 /249)
- Test impact accuracy:
  lateral 87mm left (more overlap) and vertical 7 mm lower

Test vehicle status:

- Safety systems: 3 point belt system with pretensioner (retractor & buckle) and load limiter, dual stage airbag driver/passenger, knee airbag driver, side and window airbag
- Wheels: steel, 175/65 R14, 2.2 bar
- *Ride height measurements:*
  FL: 634 mm, FR: 633 mm
  RL: 618 mm, RR: 620 mm

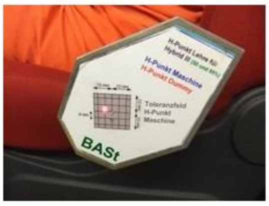
Pre-test Pictures Vehicle

Pre-test Pictures
Barrier

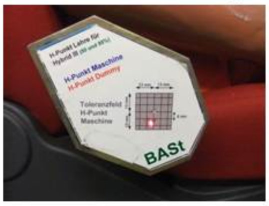


Additional Pre-test pictures

H-Point Driver



H-Point Passenger



Description of front-end structure

Three front load paths

- *Upper load path: Frontend assembly/radiator support at bonnet leading edge*
- *Lower load path: Longitudinals / crush can/ bumper crossbeam → PEAS*
- *3rd load path: Sub frame/crush can/crossbeam → SEAS*
- *Vertical connection between all load paths*

Dimensions [mm] (heights above ground)	Top height	Bottom height	Width	Depth
Engine	737	167	470	263
Gear Box	370	160	372	-
Higher Crossbeam	661	539	-	-
Lower Crossbeam	350	300	-	-
Subframe	-	210	560	-

Vehicle / barrier results

Post-test Pictures
Vehicle

FIMCAR frontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Front End Structure

FIMCAR frontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures Barrier

Additional Post-test pictures

Static deformation in x-direction

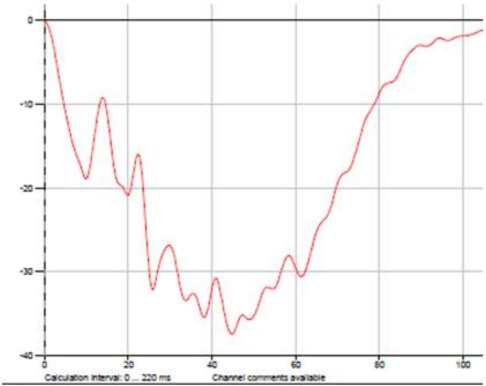
Location	Difference x	y	z
A-post-RHS-waist	0,51	5,72	3,82
A-post-RHS-sill	1,44	4,77	2,26
B-post-RHS-waist	1,23	0,54	0,57
B-post-RHS-sill	0,17	0,69	0,46
A-post-LHS-waist	2,76	2,22	0,76
A-post-LHS-sill	0,74	1,69	0,30
B-post-LHS-waist	0,12	2,35	2,40
B-post-LHS-sill	0,60	2,04	2,05
Centre of the accelerator pedal	5,99	37,57	21,24
Centre of the brake pedal	27,46	2,33	12,16
Centre of the clutch pedal	88,10	7,05	30,39
Centre of the steering column	14,57	0,84	11,96

FIMCAR frontal impact and compatibility assessment research

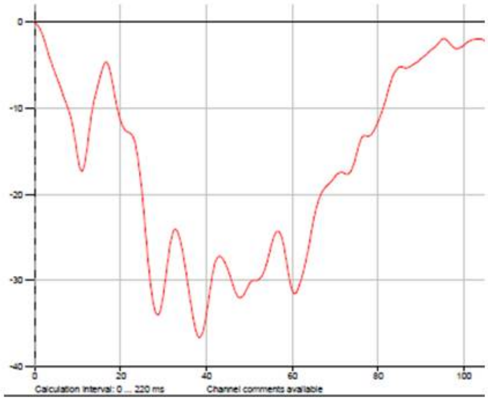
SEVENTH FRAMEWORK PROGRAMME

Vehicle Accelerations in X

A-Pillar lower left



A-Pillar lower right



FIMCAR frontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

PDB barrier deformation results

PDB barrier deforma

scans available in three resolution:

- high (1 mm)
- mid (2 mm)
- low (5 mm)

Dummy results

SEVENTH FRAMEWORK PROGRAMME

Dummy criteria Comparison

Supermini 2 PDB-Test 60km/h FM03OPDB

M03OPDB
M03OPDB
012-04-12

Supermini 2 vs. PDB 50 Offset
Frontal Impact
Euro NCAP

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (H3)		
Head & Neck			4.000			4.000
Head						
HIC 36	934.16			355.22		
Acceleration Resultant	72.00	g	4.000	45.64	g	4.000
3ms cumulative	70.30	g		44.83	g	
Neck						
Shear Force Fx+	0.91	kN	4.000	0.43	kN	4.000
Shear Force Fx-	-0.38	kN	4.000	-0.30	kN	4.000
Tensile Force Fz+	1.86	kN	4.000	1.26	kN	4.000
Extension My-	-16.76	Nm	4.000	-16.16	Nm	4.000
Chest			1.966			2.947
Deflection	-36.24	mm	1.966	-29.37	mm	2.947
VC max	0.23	m/s	4.000	0.19	m/s	4.000
belt at upper diagonal belt Force	4.19	kN		3.97	kN	

FM02OPDB
FM02OPDB
2012-01-26

Supermini 2 vs. PDB 50 Offset
Frontal Impact
Euro NCAP

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (H3)		
Femur & Knee			2.875			4.000
Left						
Femur Force Fz-	-0.66	kN	4.000	-0.53	kN	4.000
Knee Slider Displacement	-0.97	mm	4.000	-0.06	mm	4.000
Right						
Femur Force Fz-	-2.46	kN	4.000	-0.47	kN	4.000
Knee Slider Displacement	-8.53	mm	2.875	-0.18	mm	4.000
Tibia			3.091			2.540
Left						
Compression Upper Fz-	-1.26	kN	4.000	-2.51	kN	3.658
Compression Lower Fz-	-1.45	kN	4.000	-3.47	kN	3.023
Tibia Index Upper	0.46		3.745	0.73		2.540
Tibia Index Lower	0.24		4.000	0.44		3.819
Right						
Compression Upper Fz-	-1.91	kN	4.000	-1.62	kN	4.000
Compression Lower Fz-	-2.04	kN	3.975	-2.00	kN	4.000
Tibia Index Upper	0.60		3.091	0.51		3.510
Tibia Index Lower	0.25		4.000	0.43		3.875
Sum			11.932			13.487

SEVENTH FRAMEWORK PROGRAMME

Dummy criteria Comparison

PDB-Test 60km/h

Body Region	SP 1	SP 3
Head & Neck	4.000 *	4.000 *
Chest	1.966 *	2.947 *
Femur & Knee	2.875 *	4.000 *
Tibia	3.091 *	2.540 *
Sum	11.932	13.487

EuroNCAP ODB-Test 64 km/h

SUMMARY

Supermini 2

Adult Occupant Rating

Frontal Driver	
Head and Neck assessment	4.00
Chest assessment	3.82
Knee, Femur and Pelvis assessment	4.00
Lower Leg, Foot and Ankle assessme	3.29
Frontal Passenger	
Head and Neck assessment	4.00
Chest assessment	3.94
Knee, Femur and Pelvis assessment	4.00
Lower Leg assessment	3.84
Door Opening	0
OVERALL FRONT	15.11

Firing times

- Driver Airbag:
  Stage 1 at 18,9 ms
  Stage 2 at 22,5 ms

13 CITY CAR 1 PDB 60 KM/H @ UTAC

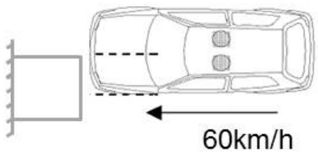
Offset Test
Citycar 1 vs PDB

AFFSEP1102347

Analysis and Report

PDB 'Citycar1'

Test Date:	09, 2011
Location:	UTAC
Topic:	PDB-Test
Mass Ratio:	N/A
Test Number:	**AFFSEP1102347**
Test Protocol:	N/A

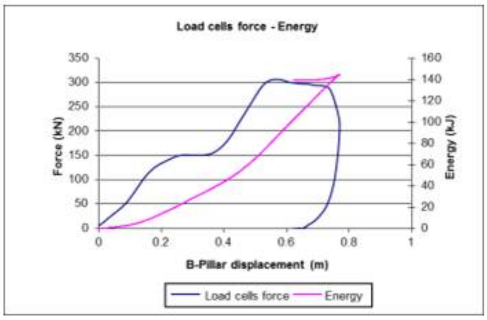


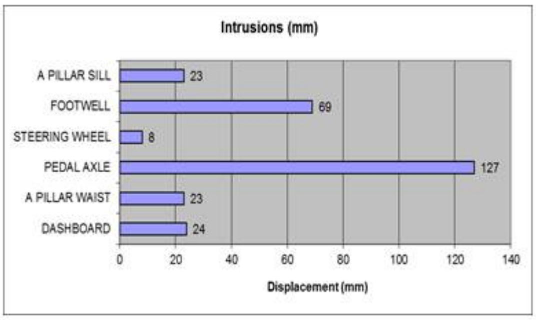
Vehicle 1:	Super Mini	Barrier: PDB v8
Brand/type:	Citycar 1	
Engine	1.2L, 4 cylinders	
Impact side:	Front left	
Speed:	60,06 km/h	
Overlap:	50 %	
Test mass:	1168.0 kg	
Dummy:	LHS – HIII 50% RHS – HIII 50%	

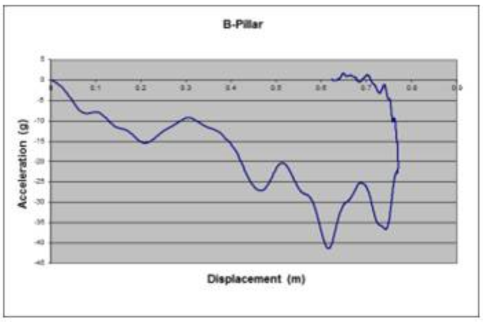
Test objective: Frontal crash to PDB with a 50% overlap at 60km/h

2- SELF PROTECTION : Structural analysis (1/2)

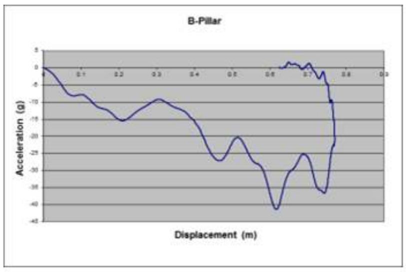
Average intrusion
53,2 mm up = 23,5mm low=73mm
Maximum force
306 kN
EES
50.4 km/h

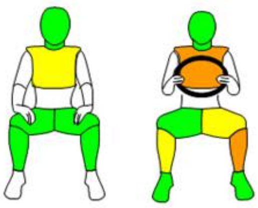






2- SELF PROTECTION : Dummies (2/2)



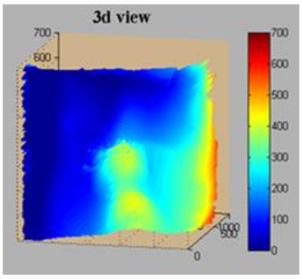


* Rating representation

		DRIVER	PASS	ECE R94
Head	HIC	506	442	<1000
	Criteria 3ms (g)	51,6	50,5	<80g
Upper Neck	NIC	<corridor		<corridor
	My (Nm)	45,8	19,3	<57 Nm
Chest	Deflexion (mm)	33	24,2	<50mm
	Viscous criterion	0,195	0,103	<1 m/s
Femur	Force	<corridor		<corridor
Knee	Left disp, (mm)	1,89	3,51	<15mm
	Right disp, (mm)	3,58	0,04	<15mm
Tibia Index	Left upper	0,38	0,23	<1,3
	Left lower	0,69	0,15	<1,3
	Right upper	0,81	0,36	<1,3
	Right lower	0,60	0,19	<1,3

Dummies criteria far from R94 limits

3- PARTNER PROTECTION ANALYSIS: PDB (1/2)



MAX DEFORMATION	VOLUME	ENERGY
425 mm	104 dm3	47,7 kJ

Homogeneous barrier deformation

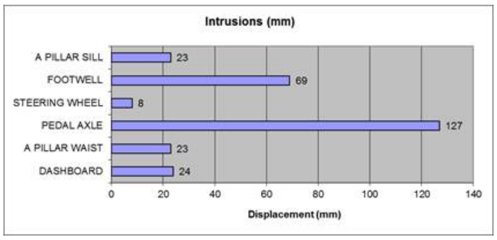
Deformation shape allows to see PEAS and SEAS

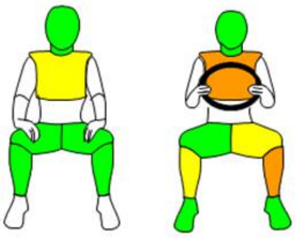
* Calculated with current formula

3- PARTNER PROTECTION ANALYSIS: Front end (2/2)

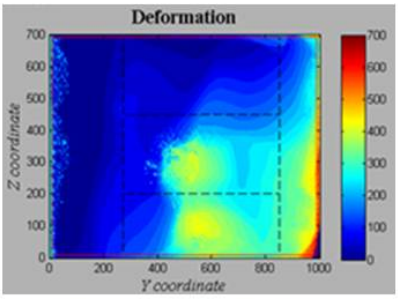
4- PARTNER AND SELF PROTECTION ASSESSMENTS

SELF

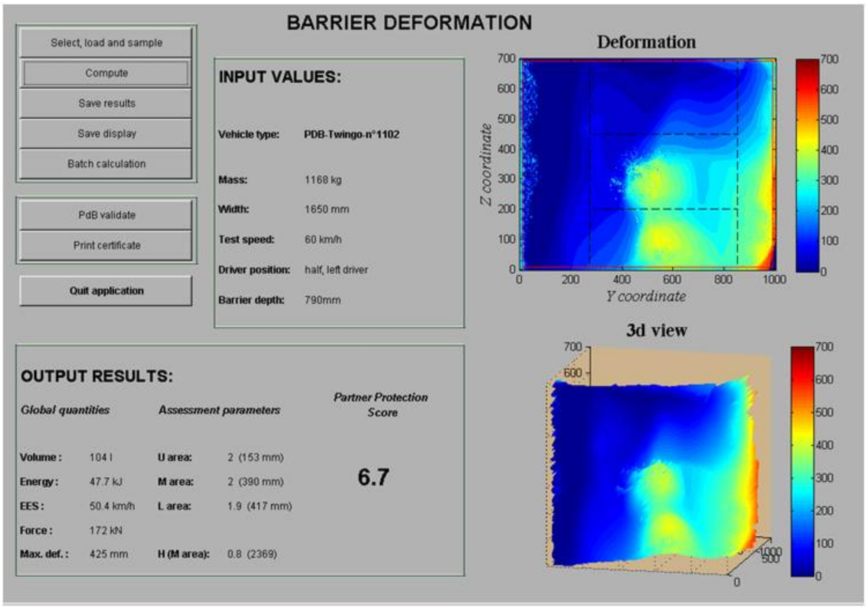




PARTNER



4- BACK UP



14 SMALL FAMILY CAR 1 PDB 60 KM/H @ IDIADA

WP2 testing activities
Small Family Car 1
PDB at IDIADA

frontal impact and compatibility assessment research

Small Family Car 1 PDB test

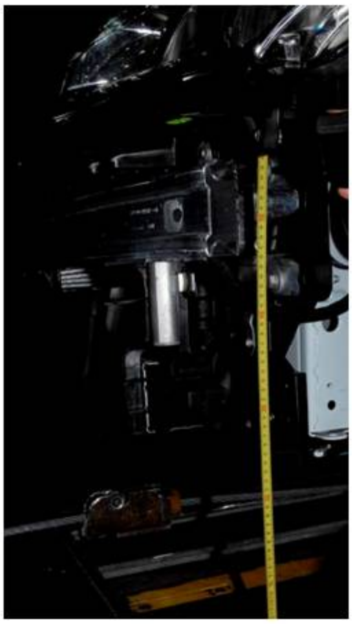
Test Date	June 28, 2012
Location	IDIADA
Topic	PDB
Mass Ratio	NA
Test Number	122611DF
Test Protocol	FIMCAR

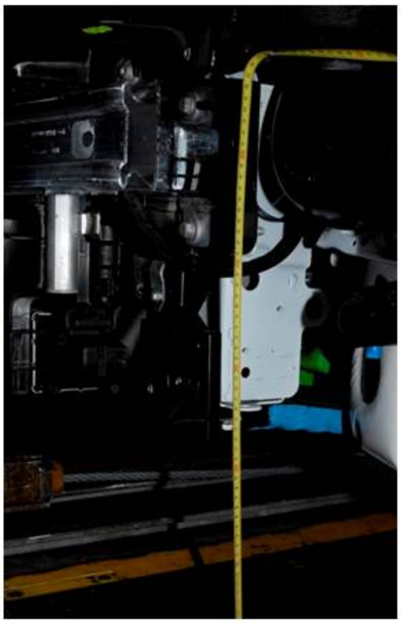
60 km/h

Vehicle 1:	Compact	Ride height measured at wheel arch:
Brand/type:	Small Family Car 1	
Impact side:	Front left	Front left: 679 mm
Speed:	60 km/h	Front right: 674 mm
Overlap:	50 %	
Test mass:	1490.0 kg	Rear left: 667 mm
Dummy:	LHS – HIII 50%	Rear right: 664 mm
	RHS – HIII 50%	

Test objective: Frontal crash to PDB with a 50% overlap at 60km/h

Small Family Car 1 PDB Test
Pre-Test measurements





PDB left impact test on Small Family Car 1

Test conditions
IDIADA test number: 122611DF
Vehicle: Small Family Car 1
Test Vehicle Mass: 1490.0 kg
Test velocity: 60.42 km/h

Euro NCAP modifiers not applied

SUMMARY	Driver	Passenger
Head and Neck assessment	4,000	4,000
Chest assessment	2,657	2,293
Knee, Femur and Pelvis assessment	4,000	4,000
Lower Leg, Foot and Ankle Assessment	3,800	3,733
TOTAL	14,457	14,026
Door Opening	0,00	
TOTAL FRONTAL	**14,026**	

Small Family Car 1 PDB Test
Pre-Test photos

Small Family Car 1 PDB Test
Static measurement results

- No door opening during the test.
- No door opening after the test.

STATIC MEASUREMENTS

+ve= up,aft,left

STEERING WHEEL	
Fore/aft displacement - mm	-26
Vertical displacement - mm	-14
Lateral displacement - mm	6

A PILLAR	
Waistline displacement - mm	9

PEDAL DISPLACEMENTS	
Brake Vertical displacement - mm	-30
Brake Horizontal displacement - mm	-29
Clutch Vertical displacement - mm	24
Clutch Horizontal displacement - mm	61
Accel Vertical displacement - mm	1
Accel Horizontal displacement - mm	29
MAXIMUM PEDAL MOVEMENT	
Brake vertical displacement - mm	-30
Clutch horizontal displacement - mm	61

DOOR APERTURE	
Waist level collapse - mm	-10
Sill level collapse - mm	-1

Small Family Car 1 PDB Test
Dummy results

Small Family Car 1

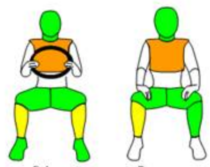
		Points		Points
HEAD				
Peak resultant acceleration - g	48,94	4,000	56,07	4,000
HIC_{36}	387,26		471,60	
Resultant Acc. 3 msec exeedence - g	47,83		54,87	
Unstable airbag contact, Bottoming out or Hazardous deployme		0,000		0,000
Steering wheel displacement (-1) mm	-1	0,000		
Incorrect airbag deployment		0,000		0,000
Head Assessment		4,000		4,000
NECK				
Shear level exceeded - kN	0,47	4,000	0,30	4,000
duration of exceedence - ms	0		0,00	
Tension level exceeded - kN	0,78	4,000	1,17	4,000
duration of exceedence - ms	0		0,00	
Extension - Nm	11,30	4,000	10,33	4,000
Neck Assessment		4,000		4,000
Head and Neck Assessment		**4,000**		**4,000**
CHEST				
Compression - mm	31,40	2,657	33,95	2,293
Viscous criterion - m/s	0,17	4,000	0,12	4,000
Steering wheel contact (-1)		0,000		
A-Pillar displacement (-2) mm	2	0,000		
Unstable passenger compartment (-1)		0,000		
Shoulder belt load - kN	4,40		4,26	
Chest Incorrect Airbag Deployment Modifier		0,000		0,000
Chest Assessment		**2,657**		**2,293**

		Points		Points
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0,0	4,000	1,0	4,000
Left Femur Compression level exceeded - kN	0,41	4,000	1,5	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Left Knee, Femur and Pelvis Assessment		4,000		4,000
Right Knee Slide - mm	0,2	4,000	0,2	4,000
Right Femur Compression level exceeded - kN	0,46	4,000	2,3	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Right Knee, Femur and Pelvis Assessment		4,000		4,000
Knee, Femur and Pelvis assessment		**4,000**		**4,000**
LOWER LEG				
Left compression - kN	1,77	4,000	1,99	4,000
Left Upper Tibia Index	0,42	3,911	0,26	4,000
Left Lower Tibia Index	0,28	4,000	0,28	4,000
Brake pedal vertical (-1) mm	-53	0,000		
Left Lower Leg assessment		3,911		4,000
Right compression - kN	2,30	3,800	1,97	4,000
Right Upper Tibia Index	0,38	4,000	0,46	3,733
Right Lower Tibia Index	0,21	4,000	0,16	4,000
Brake pedal vertical (-1) mm	-53	0,000		
Right Lower Leg assessment		3,800		3,733
FOOT and ANKLE				
Brake pedal horizontal displacement - mm	-58	4,000		
Footwell Rupture (-1)		0,000		
Pedal Blocking (-1)	22	0,000		
Foot and Ankle assessment		4,000		
Lower Leg, Foot and Ankle assessment		**3,800**		**3,733**

PDB left impact test on Small Family Car 1
Comparison results with Euro NCAP

PDB results (IDIADA)

Euro NCAP modifiers not applied



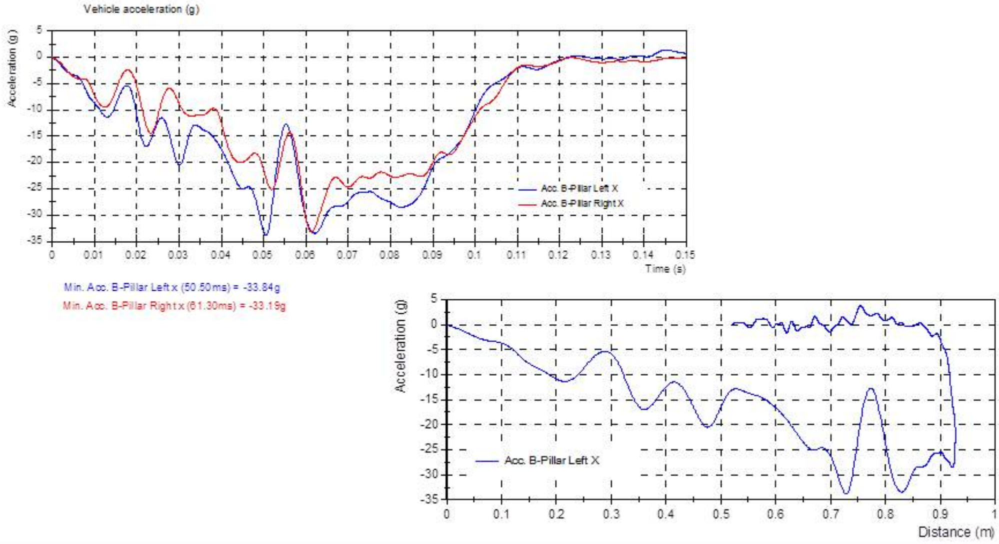
SUMMARY		
Head and Neck assessment	4,000	4,000
Chest assessment	2,657	2,293
Knee, Femur and Pelvis assessment	4,000	4,000
Lower Leg, Foot and Ankle Assessment	3,800	3,733
TOTAL	14,457	14,026
Door Opening	0,00	
TOTAL FRONTAL	**14,026**	

ODB results (Euro NCAP)

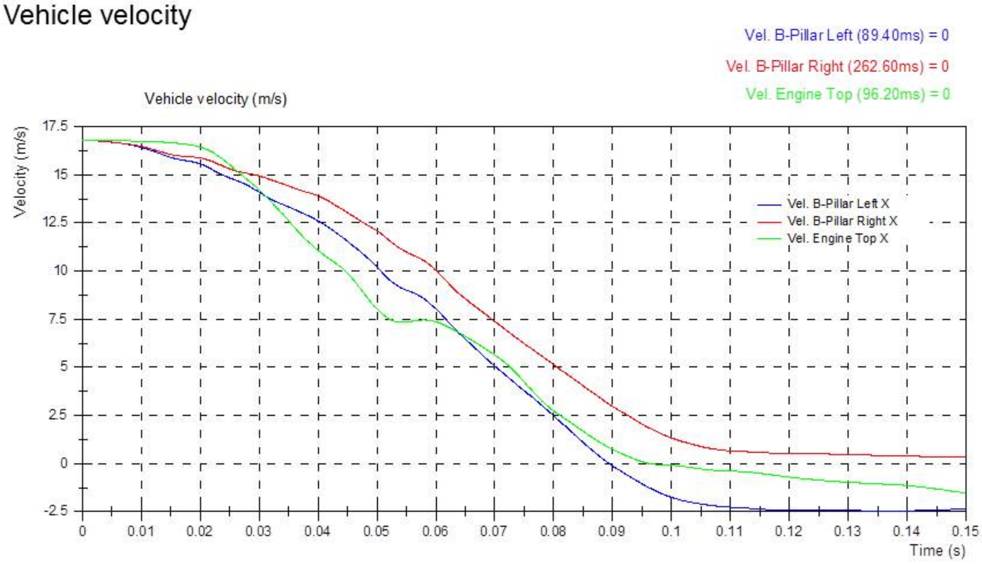
Euro NCAP modifiers applied

TOTAL FRONTAL **15,8**

Small Family Car 1 PDB Test
Vehicle pulse



Small Family Car 1 PDB Test
Vehicle velocity



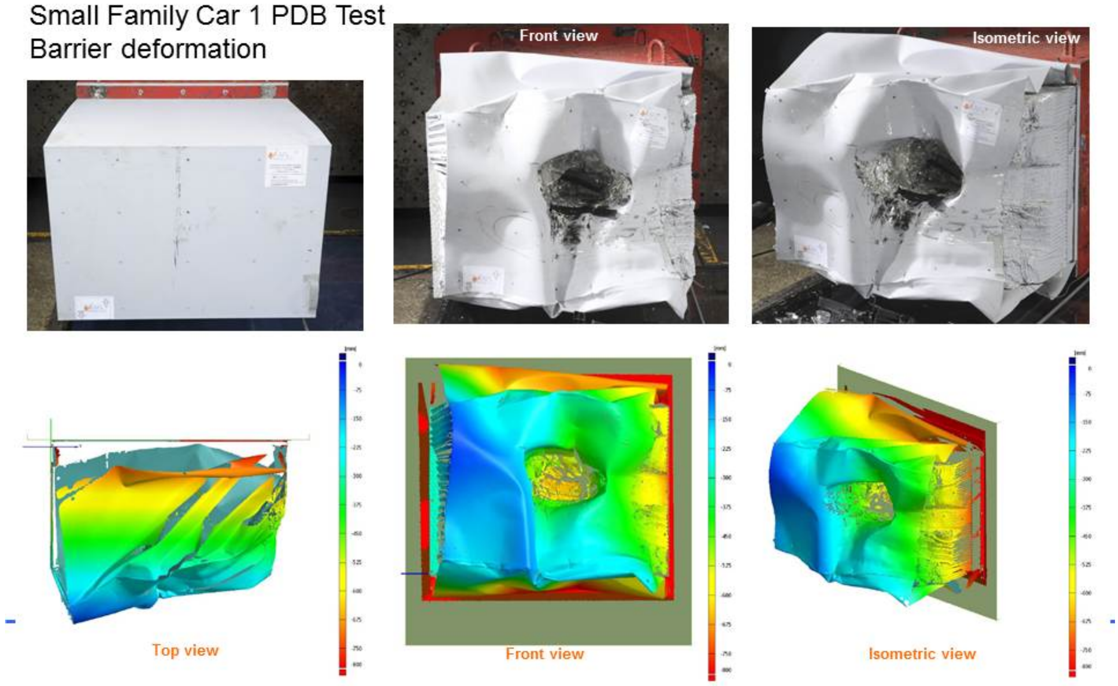
Small Family Car 1 PDB Test
Post-Test photos

Small Family Car 1 PDB Test
Post-Test photos (measurements)

FIMCAR frontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

Small Family Car 1 PDB Test
Barrier deformation



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SEVENTH FRAMEWORK PROGRAMME

Small Family Car 1 PDB Test
Conclusions

- Dummies injuries are below R94 limits
- A-Pillar waistline had only 9 mm rearward displacement
- PDB scan to be further analyzed

15 SUV 1 PDB 60 KM/H @ IDIADA

WP2 testing activities
SUV 1
PDB at IDIADA

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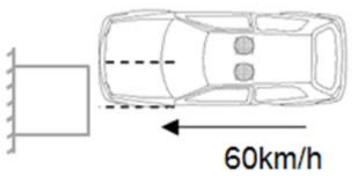
SUV 1 PDB test

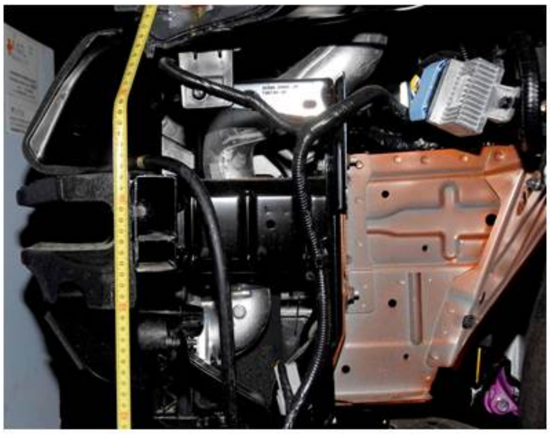
Test Date	May 28, 2012
Location	IDIADA
Topic	PDB
Mass Ratio	NA
Test Number	122201DF
Test Protocol	FIMCAR



Vehicle 1:	Off-road	Ride height measured at wheel arch:
Brand/type:	SUV 1	
Impact side:	Front left	Front left: 765 mm
Speed:	60 km/h	Front right: 772 mm
Overlap:	50 %	
Test mass:	1906.0 kg	Rear left: 760 mm
Dummy:	LHS – HIII 50% RHS – HIII 50%	Rear right: 760 mm

Test objective: Frontal crash to PDB with a 50% overlap at 60km/h

SUV 1 PDB Test
Pre-Test measurements



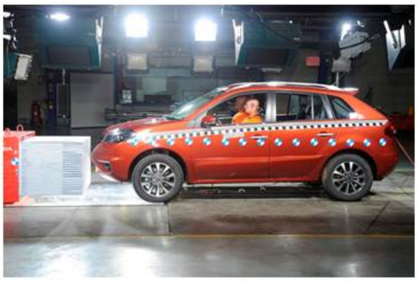
PDB left impact test on SUV 1

Test conditions
IDIADA test number: 122201DF
Vehicle: SUV 1
Test Vehicle Mass: 1906.0 kg
Test velocity: 60.34 km/h

Euro NCAP modifiers not applied

SUMMARY	Driver	Passenger
Head and Neck assessment	4,000	4,000
Chest assessment	2,266	3,389
Knee, Femur and Pelvis assessment	4,000	2,484
Lower Leg, Foot and Ankle Assessment	4,000	3,911
TOTAL	14,266	13,784
Door Opening	0,00	
TOTAL FRONTAL	12,661	

SUV 1 PDB Test
Pre-Test photos



SUV 1 PDB Test
Static measurement results

- No door opening during the test.
- No door opening after the test.

STATIC MEASUREMENTS

+ve= up aft left

STEERING WHEEL	
Fore/aft displacement - mm	-37
Vertical displacement - mm	-7
Lateral displacement - mm	-1

A PILLAR	
Waistline displacement - mm	2

PEDAL DISPLACEMENTS	
Brake Vertical displacement - mm	-53
Brake Horizontal displacement - mm	-58
Clutch Vertical displacement - mm	-11
Clutch Horizontal displacement - mm	22
Accel Vertical displacement - mm	-8
Accel Horizontal displacement - mm	10
MAXIMUM PEDAL MOVEMENT	
Brake vertical displacement - mm	-53
Brake horizontal displacement - mm	-58

DOOR APERTURE	
Waist level collapse - mm	-2
Sill level collapse - mm	-2

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SEVENTH FRAMEWORK PROGRAMME

SUV 1 PDB Test
Dummy results

SUV 1

		Points		Points
HEAD				
Peak resultant acceleration - g	37,15	4,000	37,41	4,000
HIC_{36}	238,82		223,31	
Resultant Acc. 3 msec exeedence - g	36,41		36,03	
Unstable airbag contact, Bottoming out or Hazardous deployme		0,000		0,000
Steering wheel displacement (-1) mm	-1	0,000		
Incorrect airbag deployment		0,000		0,000
Head Assessment		4,000		4,000
NECK				
Shear level exceeded - kN	0,39	4,000	0,66	4,000
duration of exceedence - ms	0		0,00	
Tension level exceeded - kN	1,09	4,000	0,94	4,000
duration of exceedence - ms	0		0,00	
Extension - Nm	13,25	4,000	25,37	4,000
Neck Assessment		4,000		4,000
Head and Neck Assessment		4,000		4,000
CHEST				
Compression - mm	34,14	2,266	26,28	3,389
Viscous criterion - m/s	0,13	4,000	0,10	4,000
Steering wheel contact (-1)		0,000		
A-Pillar displacement (-2) mm	2	0,000		
Unstable passenger compartment (-1)		0,000		
Shoulder belt load - kN	5,85		5,89	
Chest Incorrect Airbag Deployment Modifier		0,000		0,000
Chest Assessment		2,266		3,389

KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0,2	4,000	9,4	2,484
Left Femur Compression level exceeded - kN	0,13	4,000	2,2	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Left Knee, Femur and Pelvis Assessment		4,000		2,484
Right Knee Slide - mm	0,0	4,000	0,3	4,000
Right Femur Compression level exceeded - kN	0,08	4,000	0,8	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Right Knee, Femur and Pelvis Assessment		4,000		4,000
Knee, Femur and Pelvis assessment		4,000		2,484
LOWER LEG				
Left compression - kN	1,35	4,000	1,76	4,000
Left Upper Tibia Index	0,31	4,000	0,42	3,911
Left Lower Tibia Index	0,12	4,000	0,26	4,000
Brake pedal vertical (-1) mm	-53	0,000		
Left Lower Leg assessment		4,000		3,911
Right compression - kN	0,94	4,000	1,23	4,000
Right Upper Tibia Index	0,25	4,000	0,19	4,000
Right Lower Tibia Index	0,15	4,000	0,10	4,000
Brake pedal vertical (-1) mm	-53	0,000		
Right Lower Leg assessment		4,000		4,000
FOOT and ANKLE				
Brake pedal horizontal displacement - mm	-58	4,000		
Footwell Rupture (-1)		0,000		
Pedal Blocking (-1)	22	0,000		
Foot and Ankle assessment		4,000		
Lower Leg, Foot and Ankle assessment		4,000		3,911

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frontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

PDB left impact test on SUV 1
Comparison results with Euro NCAP

PDB results (IDIADA)

Euro NCAP modifiers not applied

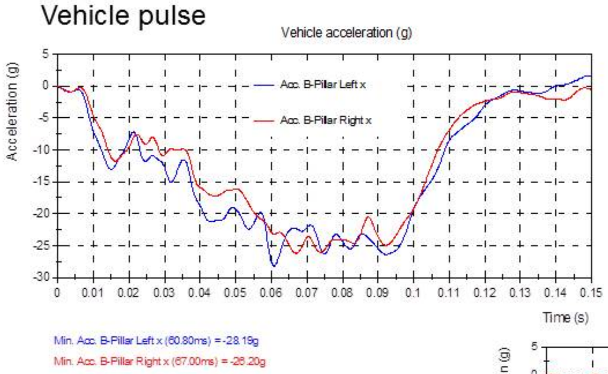
SUMMARY		
Head and Neck assessment	4,000	4,000
Chest assessment	2,266	3,389
Knee, Femur and Pelvis assessment	4,000	2,484
Lower Leg, Foot and Ankle Assessment	4,000	3,911
TOTAL	14,266	13,784
Door Opening	0,00	
TOTAL FRONTAL	**12,661**	

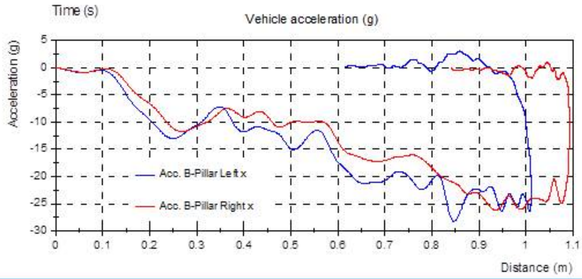
ODB results (Euro NCAP)

Euro NCAP modifiers applied

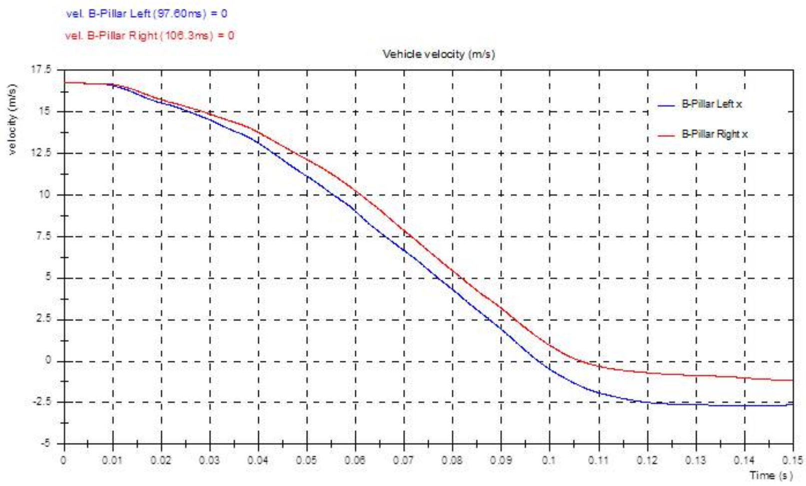
TOTAL FRONTAL 13,1

SUV 1 PDB Test
Vehicle pulse

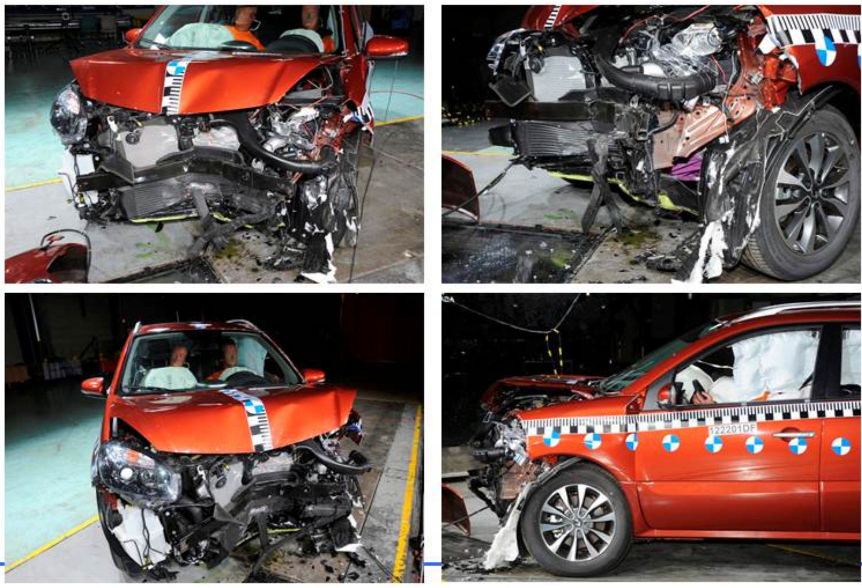




SUV 1 PDB Test
Vehicle velocity



SUV 1 PDB Test
Post-Test photos



SUV 1 PDB Test
Post-Test photos (measurements)

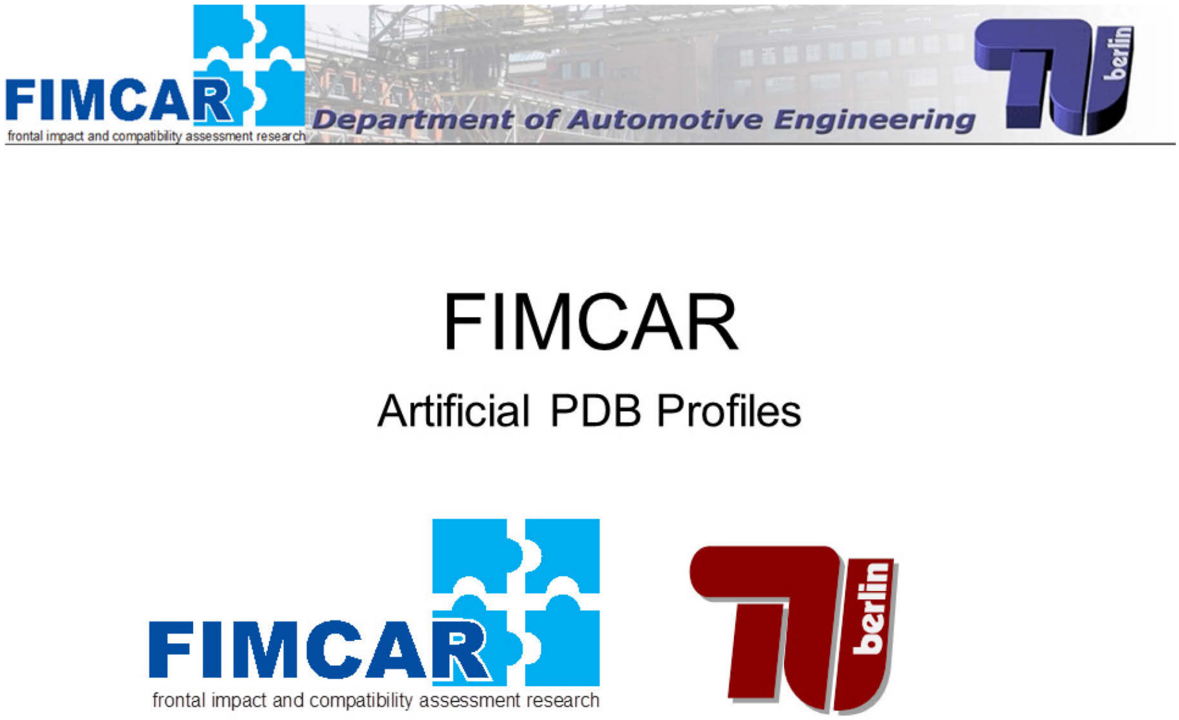
SUV 1 PDB Test
Barrier scan procedure

SUV 1 PDB Test
Barrier deformation

SUV 1 PDB Test
Conclusions

- Dummies injuries below R94 limits
- A-Pillar waistline only 2 mm rearward displacement
- PDB scan to be further analysed

ANNEX F: ARTIFICIAL PROFILES



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- **To represent different vehicle widths two average values calculated with data from the structural database were used**
  - **Super Mini car: avarage width = 1652mm ➔ y_{min} = 274mm**
  - **Off Road car: avarage width = 1842mm ➔ y_{min} = 179mm**

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- **PDB assessment metrics**
  - **BDA software v1.0**
  - **Homogeneity value (TV upgraded)**
    - A_{def}(40%)
    - Assessment of middle and lower area ➔ z_{min} = 30mm & z_{max} = 450mm
  - **DDY**
    - 60% of vehicle width
    - Assessment area w.r.t. LCW Row 3 and Row 4 (330mm-580mm) ➔ z_{min} = 180mm & z_{max} = 430mm
    - 99%ile DDY

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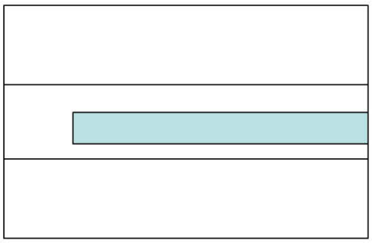
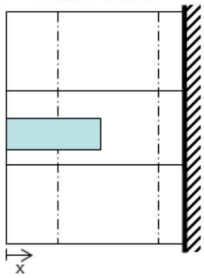
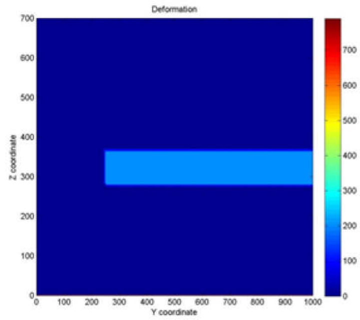
Profile 1

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	24	295	2	23	2	295	1.1	139	0	5258	5.1
179	24	295	2	23	2	295	1.1	139	0	5753	5.1

BDA software

y_{min}	M area + L area
274	13,784,463
179	13,656,662

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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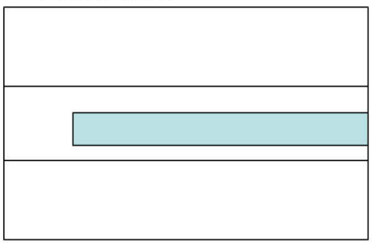
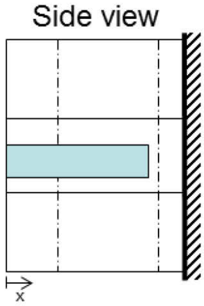
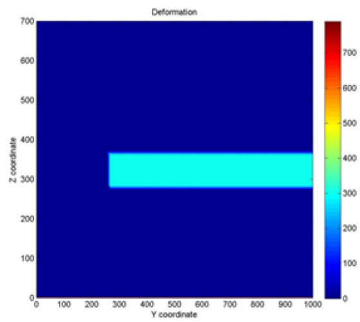
Profile 2

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	30	395	2	23	2	395	1.1	139	0	5264	5.1
179	30	395	2	23	2	395	1.1	139	0	5680	5.1

BDA software

y_{min}	M area + L area
274	10,279,939
179	9,916,783

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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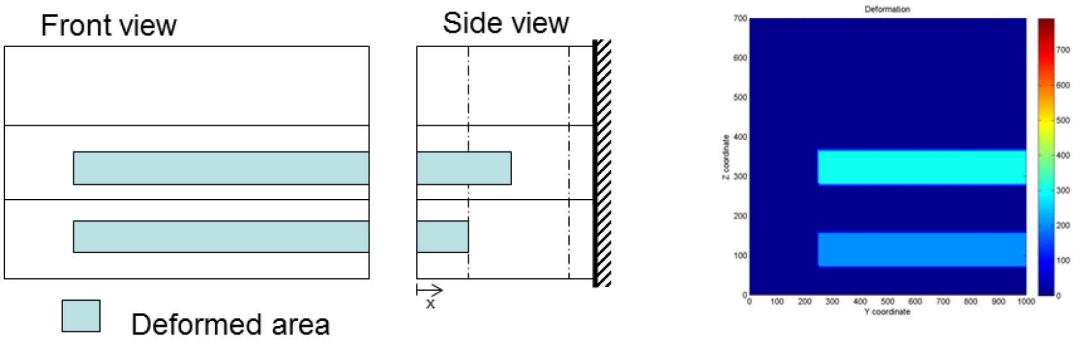
Profile 3



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	51	395	2	23	2	395	2	295	0	5260	6
179	51	395	2	23	2	395	2	395	0	5755	6

BDA software

y_{min}	M area + L area
274	23,747,366
179	23,561,656

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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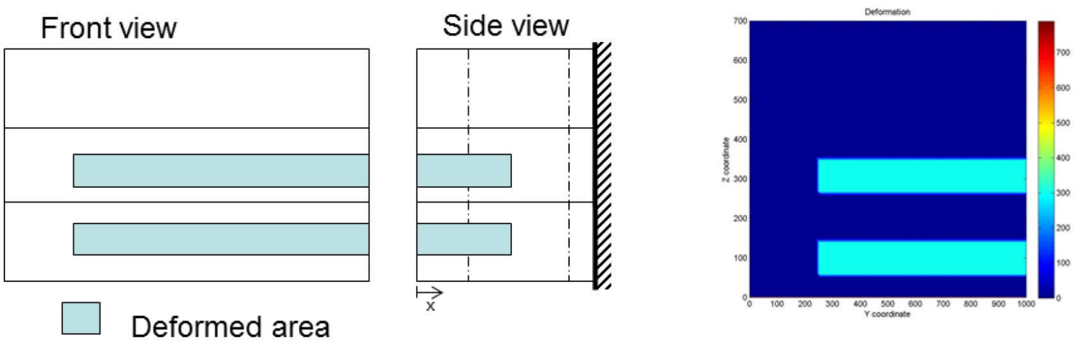
Profile 4



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	57	395	2	23	2	395	2	395	0	5240	6
179	57	395	2	23	2	395	2	395	0	5735	6

BDA software

y_{min}	M area + L area
274	20,559,878
179	20,366,140

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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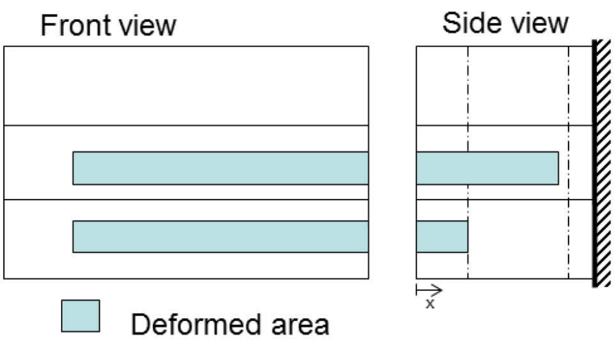
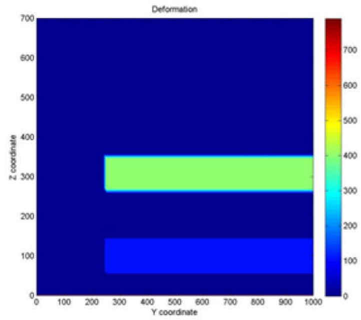
Profile 5





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	51	495	2	23	0.9	495	1.6	195	0	5241	4.5
179	51	495	2	23	0.9	495	1.6	195	0	5735	4.5

BDA software

y_{min}	M area + L area
274	8,196,167
179	8,119,866

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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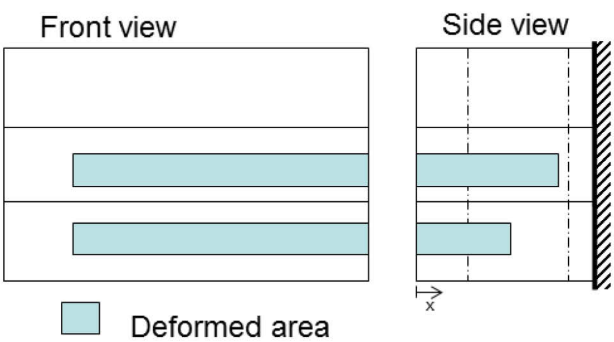
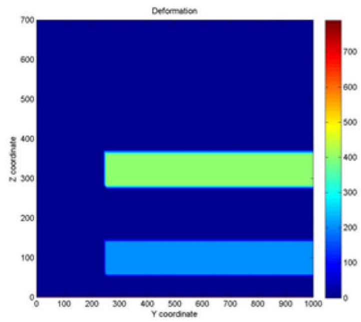
Profile 6





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	57	495	2	23	0.9	495	2	295	0	5261	4.9
179	57	495	2	23	0.9	495	2	295	0	5756	4.9

BDA software

y_{min}	M area + L area
274	21,579,290
179	21,352,871

Homogeneity value

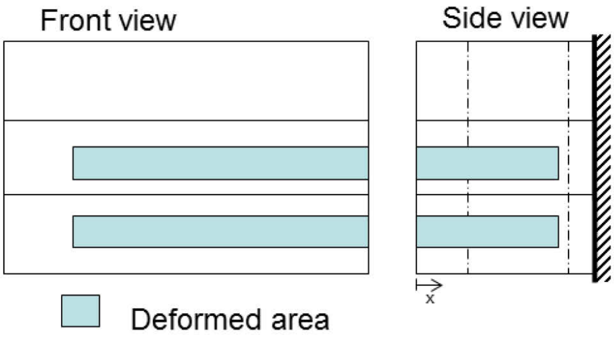
y_{min}	Row 3 + Row 4
274	0
179	0

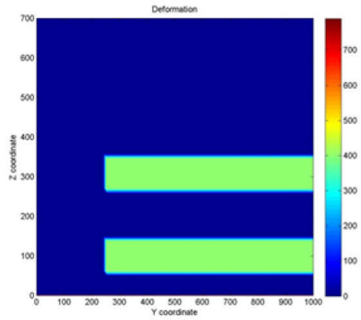
DDY

Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 9

Department of Automotive Engineering

Profile 7





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	71	495	2	23	0.9	495	1.5	495	0	5241	4.5
179	71	495	2	23	0.9	495	1.5	495	0	5737	4.5

BDA software

y_{min}	M area + L area
274	16,392,335
179	16,237,387

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 10

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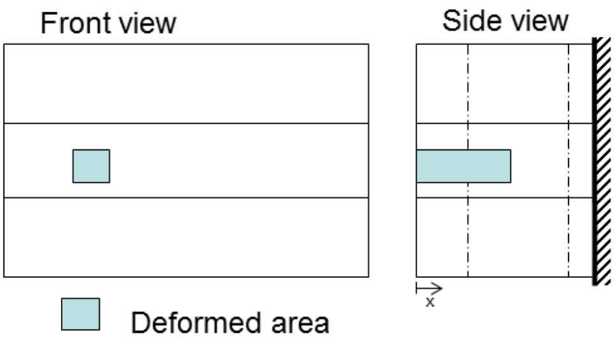
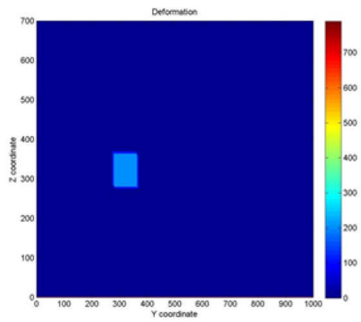
Profile 8





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	7	295	2	23	2	295	1.1	139	0	3738	5.1
179	7	295	2	23	2	295	1.1	139	0	4109	5.1

BDA software

y_{min}	M area + L area
274	1,236,732
179	1,237,340

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 11

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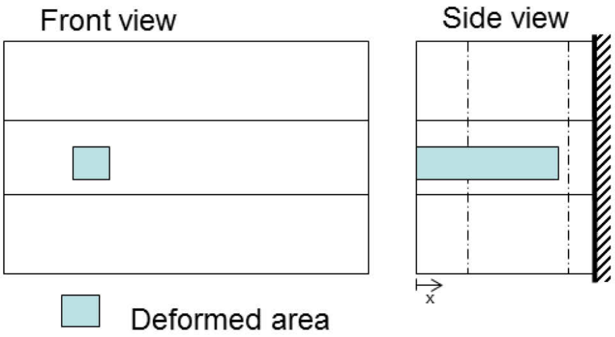
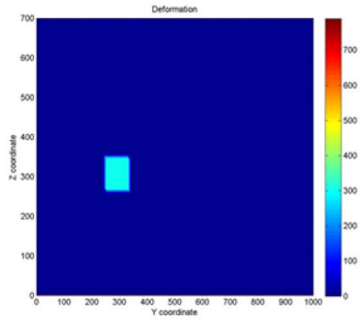
Profile 9





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	7	395	2	23	2	395	1.1	139	0.3	2951	5.4
179	7	395	2	23	2	395	1.1	139	0	4108	5.1

BDA software

y_{min}	M area + L area
274	725,859
179	922,839

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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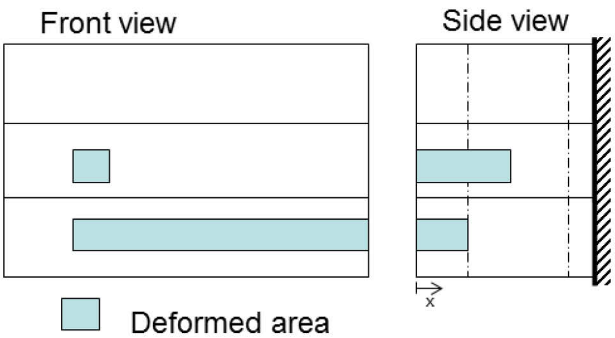
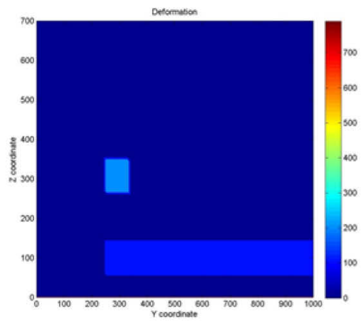
Profile 10





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	20	295	2	23	2	295	1.6	195	0.3	2950	5.9
179	20	295	2	23	2	295	1.6	195	0	4106	5.6

BDA software

y_{min}	M area + L area
274	21,865,918
179	20,952,283

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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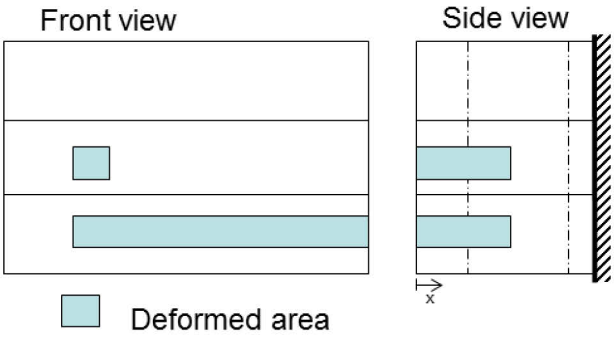
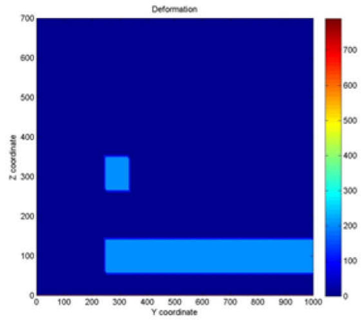
Profile 11





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	26	295	2	23	2	295	2	295	0.3	2950	6.3
179	26	295	2	23	2	295	2	295	0	4106	6

BDA software

y_{min}	M area + L area
274	14,498,970
179	14,433,905

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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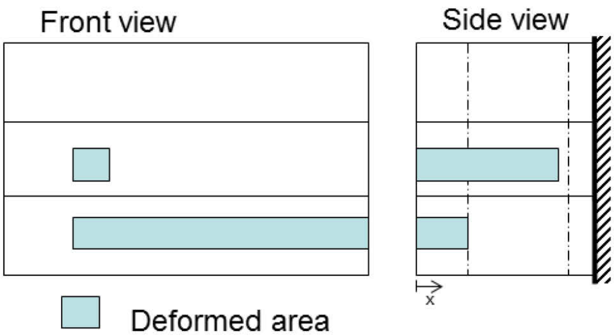
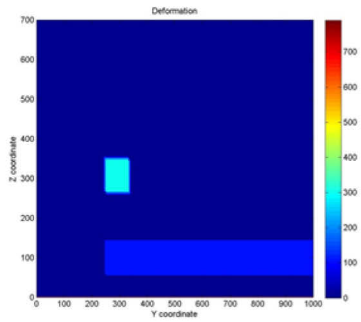
Profile 12





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	21	395	2	23	2	395	1.6	195	0.3	2951	5.9
179	21	395	2	23	2	395	1.6	195	0	4108	5.6

BDA software

y_{min}	M area + L area
274	25,464,133
179	22,497,779

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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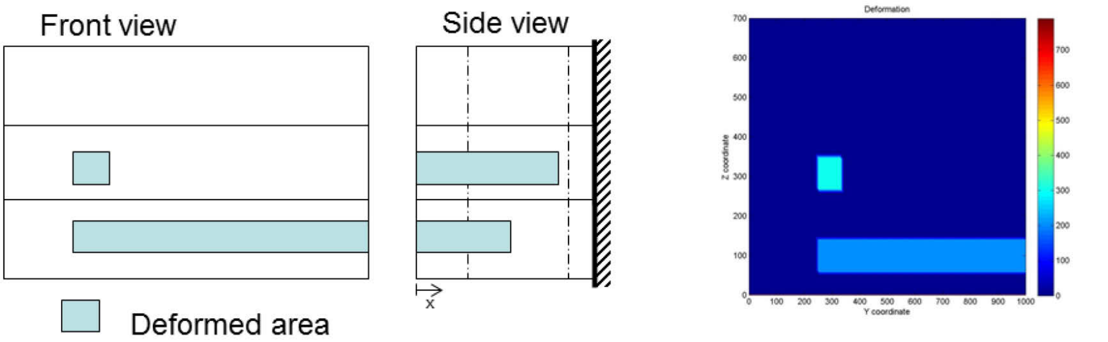
Profile 13



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	27	395	2	23	2	395	2	295	0.3	2951	6.3
179	27	395	2	23	2	395	2	295	0	4108	6

BDA software

y_{min}	M area + L area
274	14,085,462
179	13,736,080

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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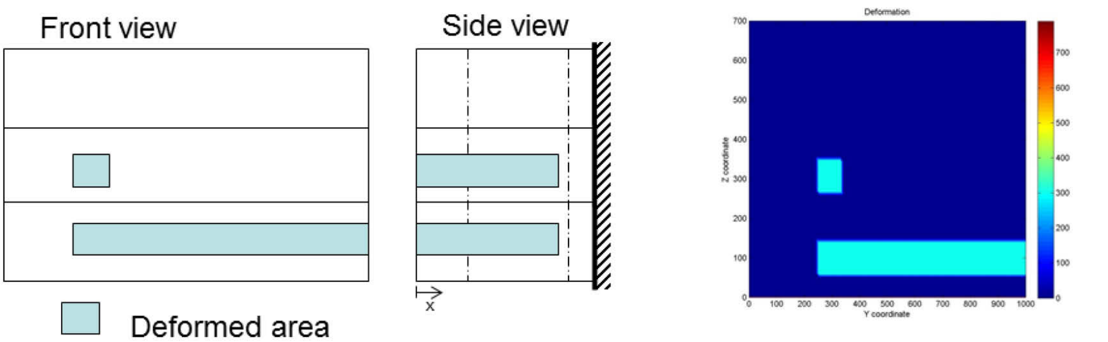
Profile 14



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	34	395	2	23	2	395	2	395	0.3	2951	6.3
179	34	395	2	23	2	395	2	395	0	4108	6

BDA software

y_{min}	M area + L area
274	10,812,289
179	10,766,022

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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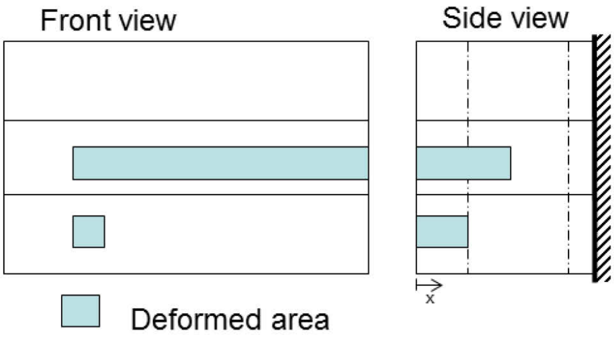
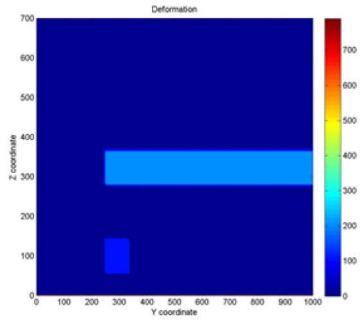
Profile 15





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	26	295	2	23	2	295	1.6	195	0	5258	5.6
179	26	295	2	23	2	295	1.6	195	0	5753	5.6

BDA software

y_{min}	M area + L area
274	15,396,278
179	15,724,373

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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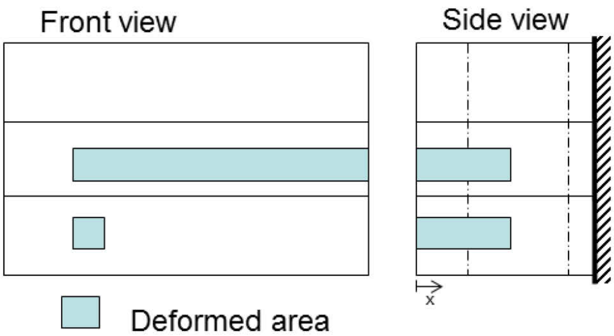
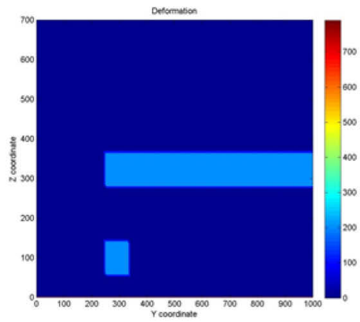
Profile 16





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	26	295	2	23	2	295	2	295	0	5258	6
179	26	295	2	23	2	295	2	295	0	5753	6

BDA software

y_{min}	M area + L area
274	14,501,685
179	14,440,103

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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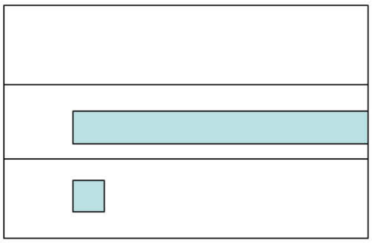
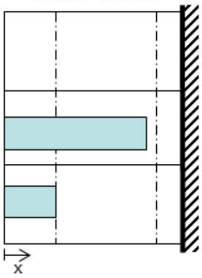
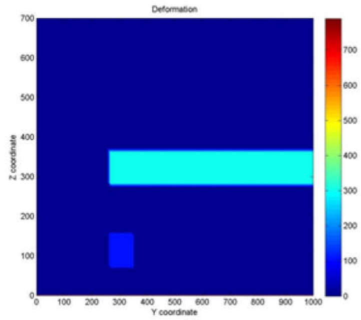
Profile 17

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	32	395	2	23	2	395	1.6	195	0	5264	5.6
179	32	395	2	23	2	395	1.6	195	0	5680	5.6

BDA software

y_{min}	M area + L area
274	12,223,898
179	11,890,413

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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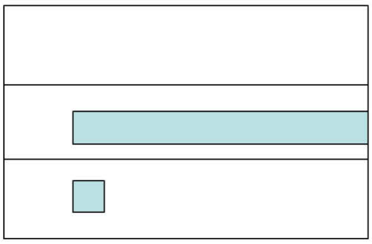
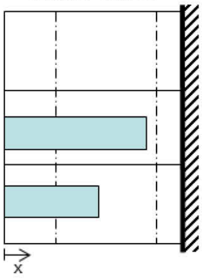
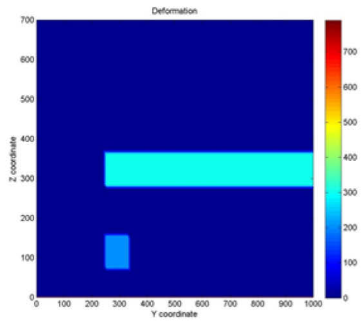
Profile 18

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	33	395	2	23	2	395	2	295	0	5260	6
179	33	395	2	23	2	395	2	295	0	5755	6

BDA software

y_{min}	M area + L area
274	11,315,870
179	11,479,789

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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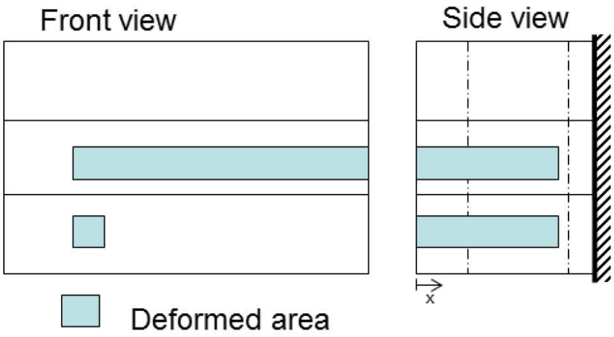
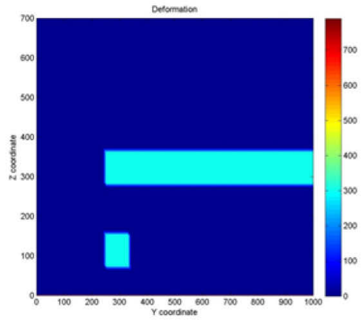
Profile 19





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	34	395	2	23	2	395	2	395	0	5260	6
179	34	395	2	23	2	395	2	395	0	5755	6

BDA software

y_{min}	M area + L area
274	10,814,675
179	10,768,078

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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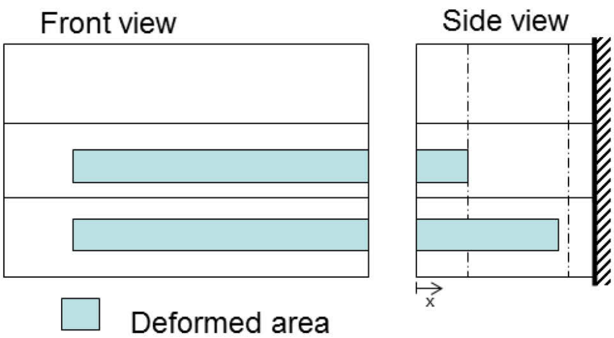
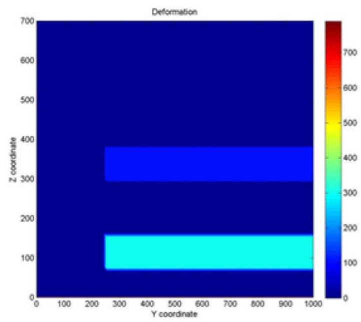
Profile 20





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	44	395	2	23	1.6	195	2	395	0	5254	5.6
179	44	395	2	23	1.6	195	2	395	0	5748	5.6

BDA software

y_{min}	M area + L area
274	29,508,035
179	29,114,740

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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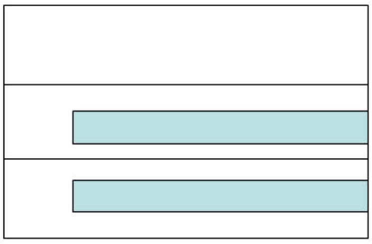
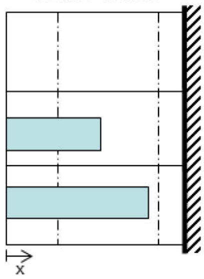
Profile 21

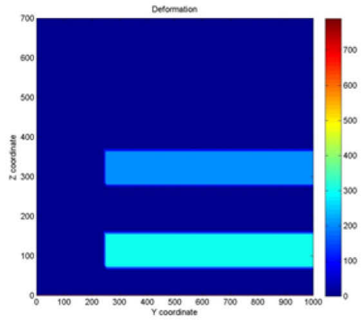
Front view



Deformed area

Side view





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	51	395	2	23	2	295	2	395	0	5258	6
179	51	395	2	23	2	295	2	395	0	5753	6

BDA software

y_{min}	M area + L area
274	23,674,984
179	23,485,518

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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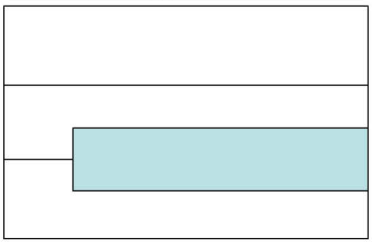
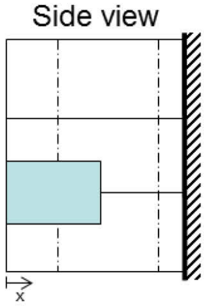
Profile 22

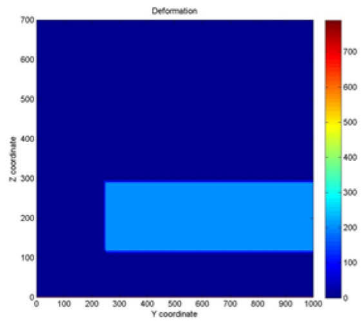
Front view



Deformed area

Side view





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	295	2	23	2	295	2	295	0.7	2527	6.7
179	44	295	2	23	2	295	2	295	0.3	2979	6.3

BDA software

y_{min}	M area + L area
274	53,354,537
179	49,439,924

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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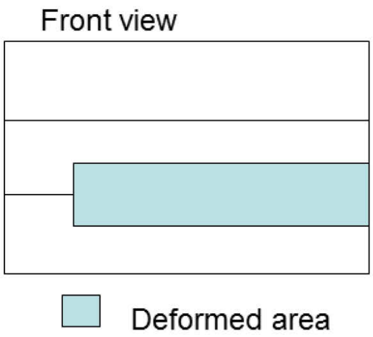
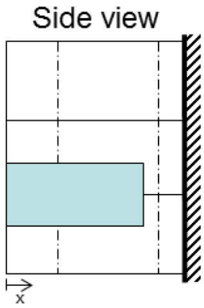
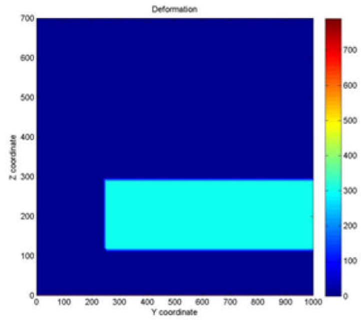
Profile 23







y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	58	395	2	23	2	395	2	395	0.7	2528	6.7
179	58	395	2	23	2	395	2	395	0.3	2980	6.3

BDA software

y_{min}	M area + L area
274	39,789,825
179	36,868,765

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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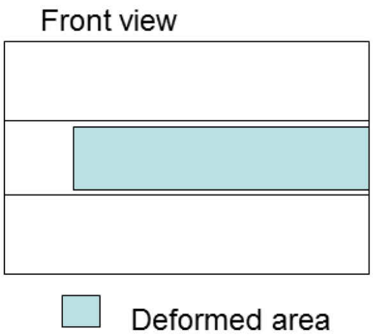
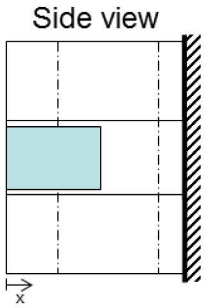
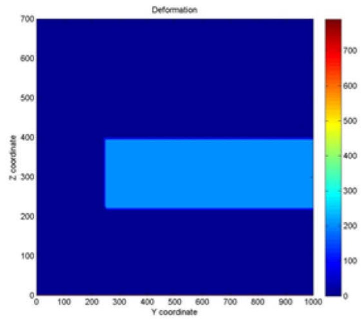
TU berlin

Profile 24







y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	295	2	23	2	295	1.1	139	0	3648	5.1
179	44	295	2	23	2	295	1.1	139	0	4269	5.1

BDA software

y_{min}	M area + L area
274	53,945,719
179	49,987,650

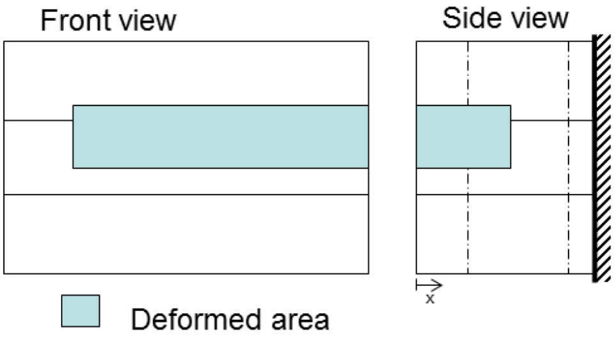
Homogeneity value

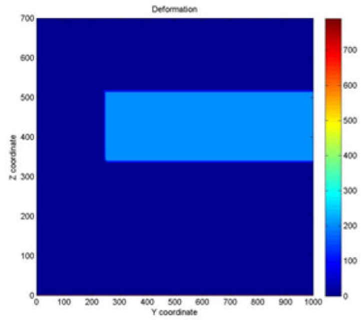
y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Department of Automotive Engineering

Profile 25





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	295	1.8	295	2	295	1.1	139	0.9	2286	5.7
179	44	295	1.8	195	2	295	1.1	139	0.5	2761	5.3

BDA software

y_{min}	M area + L area
274	43,076,448
179	38,638,517

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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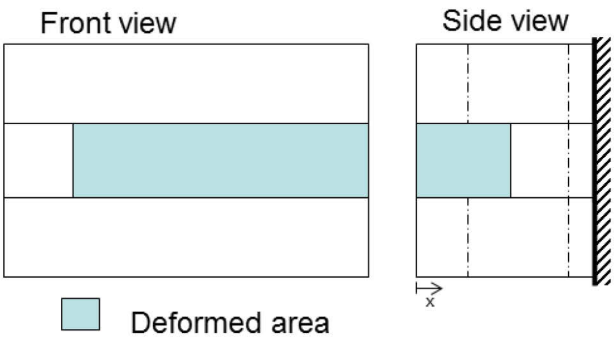
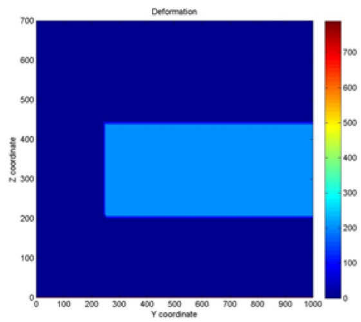
Profile 26





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	57	295	2	23	2	295	1.1	139	0.5	2730	5.6
179	57	295	2	23	2	295	1.1	139	0	3418	5.1

BDA software

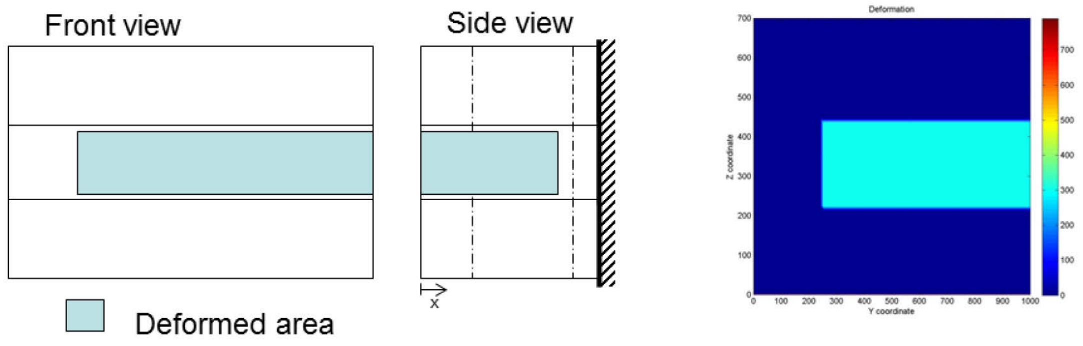
y_{min}	M area + L area
274	94,590,668
179	84,020,634

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Profile 27



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	71	395	2	23	2	395	1.1	139	0.1	3208	5.2
179	71	395	2	23	2	395	1.1	139	0	3892	5.1

BDA software

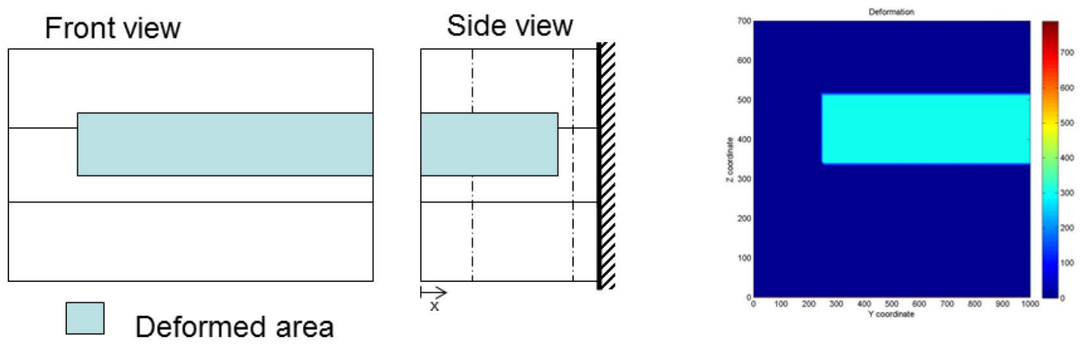
y_{min}	M area + L area
274	62,034,281
179	55,677,304

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Profile 28



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	57	395	0.1	395	2	395	1.1	139	0.9	2287	4.1
179	57	395	0.1	395	2	395	1.1	139	0.5	2762	3.7

BDA software

y_{min}	M area + L area
274	32,124,809
179	28,814,103

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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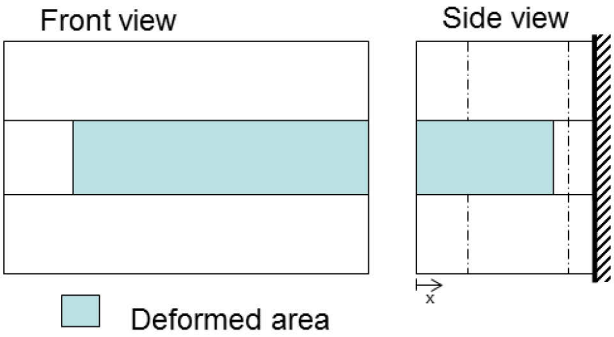
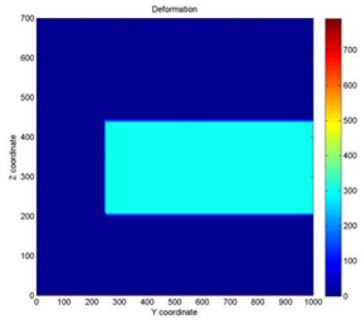
Profile 29





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	75	395	2	23	2	395	1.1	139	0.5	2731	5.6
179	75	395	2	23	2	395	1.1	139	0	3419	5.1

BDA software

y_{min}	M area + L area
274	70,542,193
179	62,656,710

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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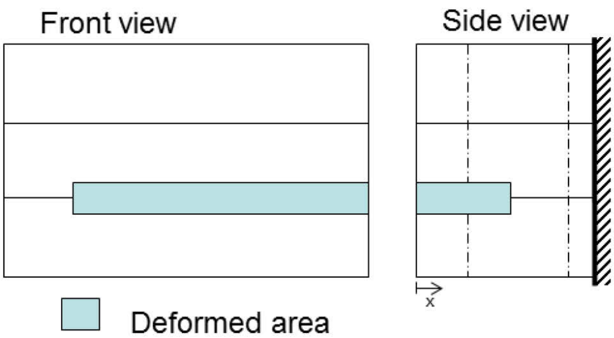
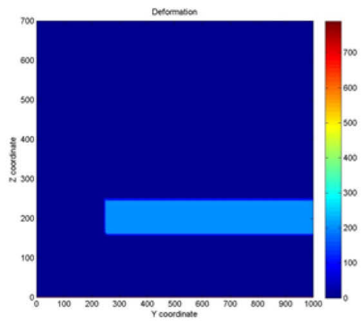
Profile 30





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	24	295	2	23	2	295	2	295	0	3571	6
179	24	295	2	23	2	295	2	295	0	3936	6

BDA software

y_{min}	M area + L area
274	13,784,463
179	13,656,623

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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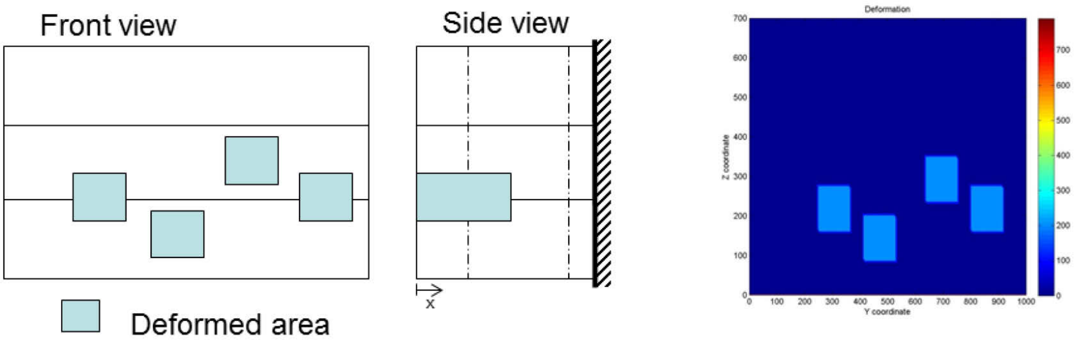
Profile 31



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	21	295	2	23	2	295	2	295	0	5560	6
179	21	295	2	23	2	295	2	295	0	5984	6

BDA software

y_{min}	M area + L area
274	9,142,383
179	9,449,795

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

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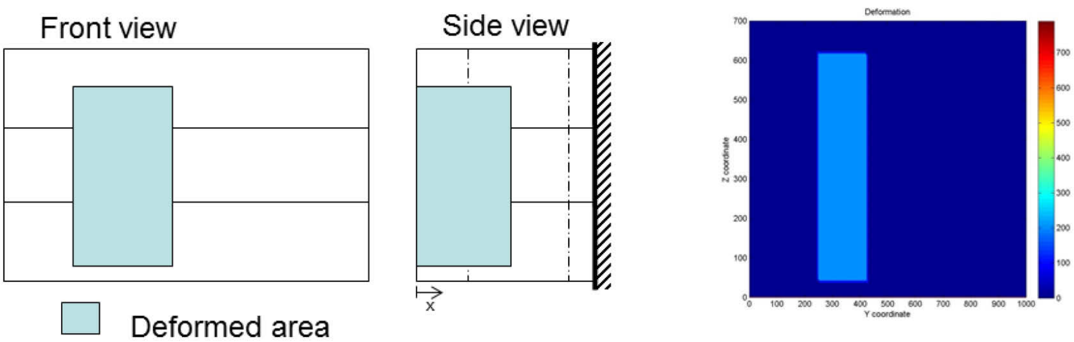
Profile 32



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	35	295	1.8	295	2	295	2	295	1.8	1297	7.5
179	35	295	1.8	295	2	295	2	295	0.8	2406	6.5

BDA software

y_{min}	M area + L area
274	40,496,337
179	32,291,821

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

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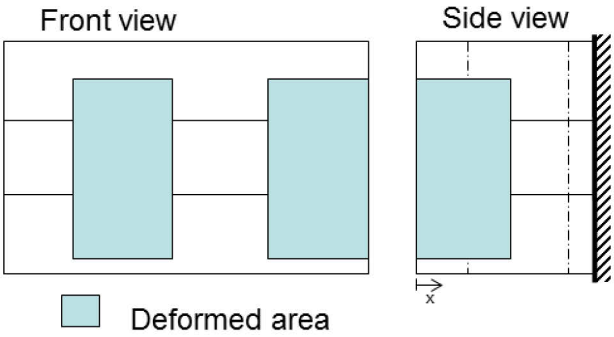
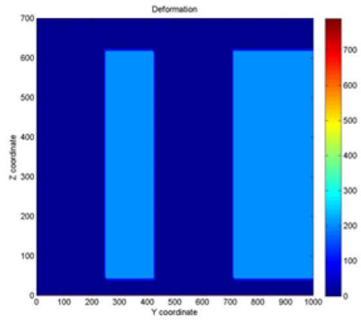
Profile 33





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	85	295	1.8	295	2	295	2	295	1.3	1866	7
179	85	295	1.8	295	2	295	2	295	0.5	2690	6.3

BDA software

y_{min}	M area + L area
274	76,604,559
179	66,378,693

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

DDY

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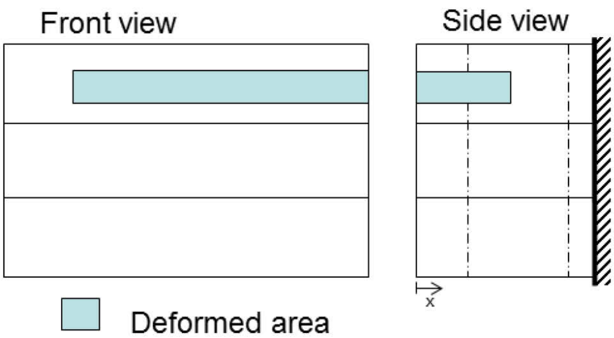
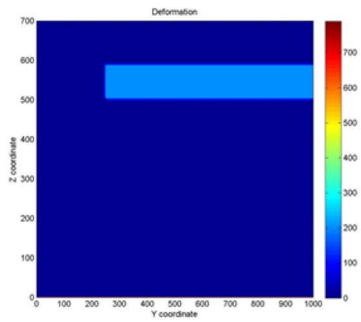
Profile 34





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	24	138	1.8	295	0	0	1.1	139	2	0	4.9
179	24	138	1.8	295	0	0	1.1	139	2	0	4.9

BDA software

y_{min}	M area + L area
274	0
179	0

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

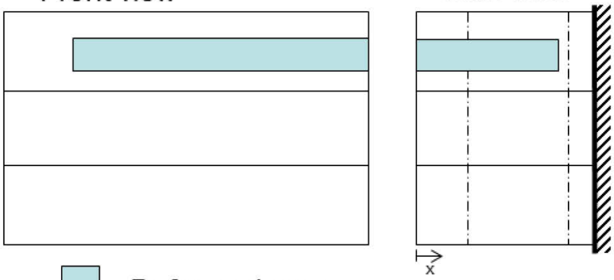
DDY

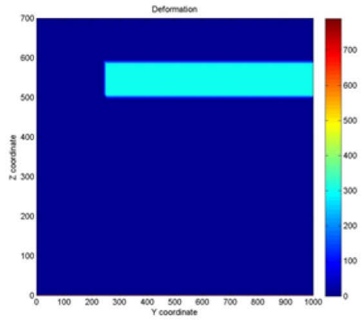
Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 37

Profile 35

Front view

Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	31	184	0.1	395	0	0	1.1	139	2	0	3.2
179	31	184	0.1	395	0	0	1.1	139	2	0	3.2

BDA software

y_{min}	M area + L area
274	0
179	0

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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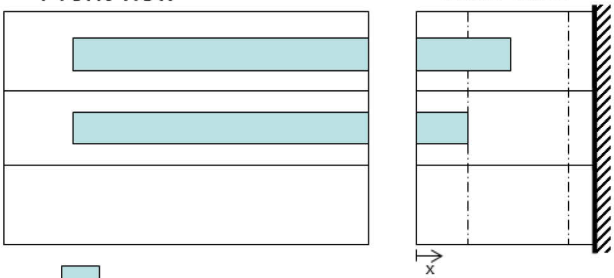
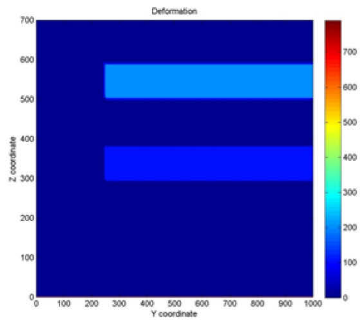
Profile 36

Front view

Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	37	195	1.8	295	1.6	195	1.1	139	0	5254	4.4
179	37	195	1.8	295	1.6	195	1.1	139	0	5748	4.4

BDA software

y_{min}	M area + L area
274	20,914,358
179	20,722,533

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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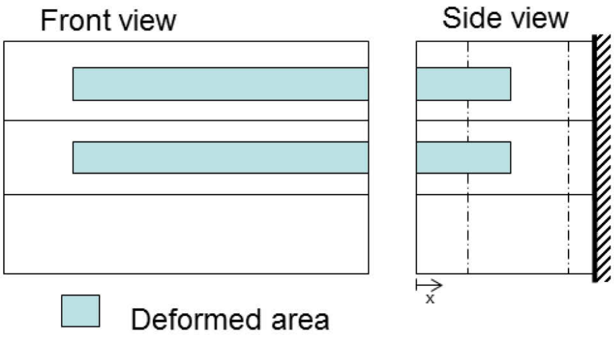
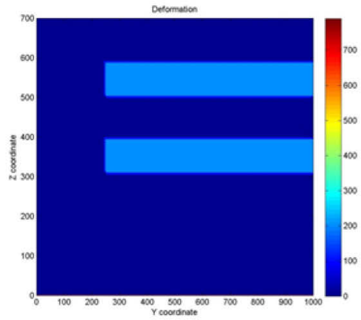
Profile 37





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	295	1.8	295	2	295	1.1	139	0	5258	4.9
179	44	295	1.8	295	2	295	1.1	139	0	5740	4.9

BDA software

y_{min}	M area + L area
274	14,085,754
179	13,951,111

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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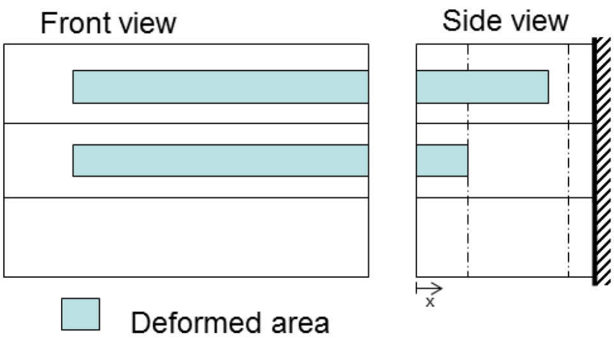
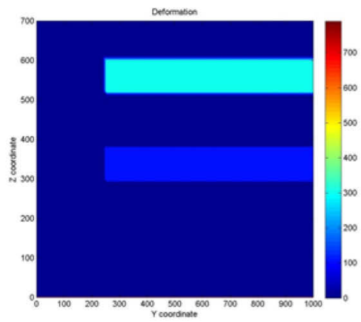
Profile 38





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	195	0.1	395	1.6	195	1.1	139	0	5254	2.8
179	44	195	0.1	395	1.6	195	1.1	139	0	5748	2.8

BDA software

y_{min}	M area + L area
274	20,914,358
179	20,722,533

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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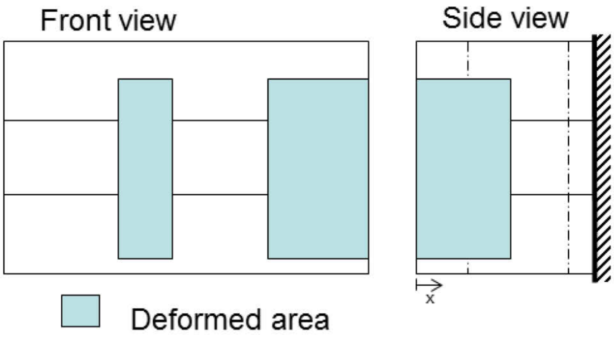
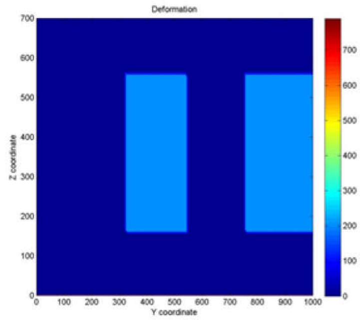
Profile 39





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	60	295	1.8	295	2	295	2	295	0.5	2690	6.3
179	60	295	1.8	295	2	295	2	295	0.5	2690	6.3

BDA software

y_{min}	M area + L area
274	20,914,358
179	43,597,516

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

DDY

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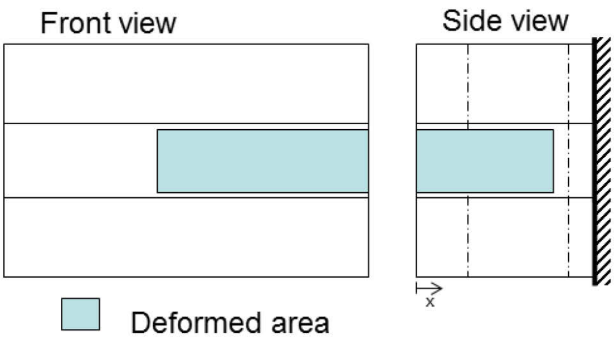
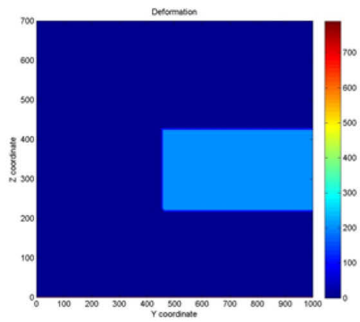
Profile 40





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	38	295	2	23	2	295	1.1	139	0	3506	5.1
179	38	295	2	23	2	295	1.1	139	0	3506	5.1

BDA software

y_{min}	M area + L area
274	40,195,514
179	40,215,247

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	20.1

DDY

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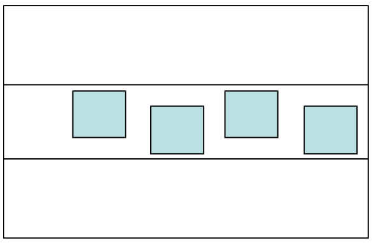
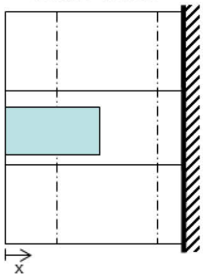
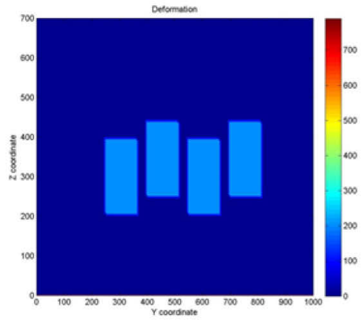
Profile 41

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	32	295	2	23	2	295	1.1	139	0	7485	5.1
179	32	295	2	23	2	295	1.1	139	0	8076	5.1

BDA software

y_{min}	M area + L area
274	21,301,336
179	21,714,007

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

DDY

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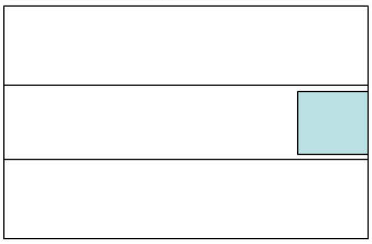
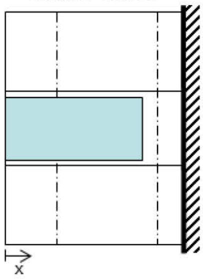
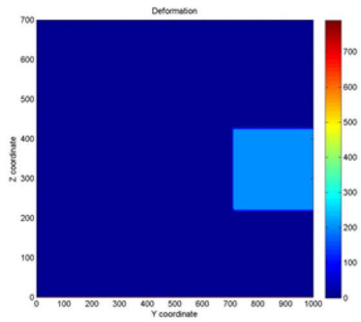
Profile 42

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	22	295	2	23	2	295	1.1	139	0.4	2864	5.5
179	22	295	2	23	2	295	1.1	139	0.4	2864	5.5

BDA software

y_{min}	M area + L area
274	10,764,362
179	10,769,647

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

DDY

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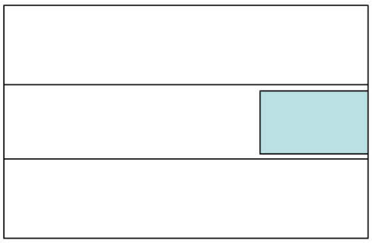
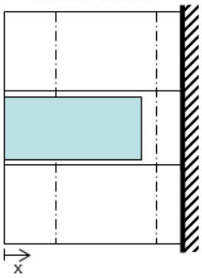
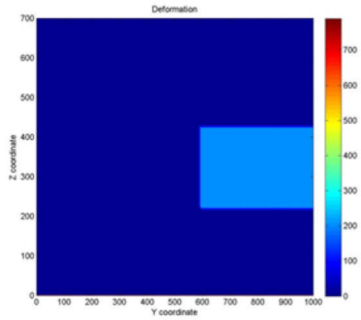
Profile 43

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	30	295	2	23	2	295	1.1	139	0.1	3153	5.2
179	30	295	2	23	2	295	1.1	139	0.1	3153	5.2

BDA software

y_{min}	M area + L area
274	24,082,267
179	24,094,090

Homogeneity value

y_{min}	Row 3 + Row 4
274	20.1
179	20.1

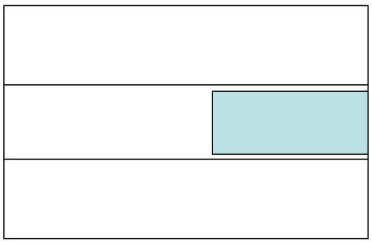
DDY

Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 46

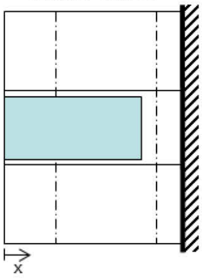
FIMCAR frontal impact and compatibility assessment research
Department of Automotive Engineering

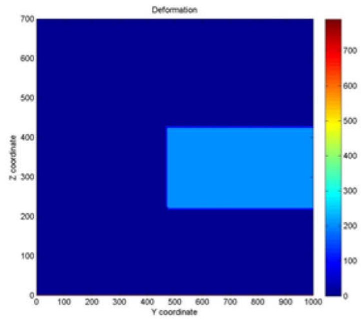
Profile 44

Front view



Side view





Deformed area

y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
274	37	295	2	23	2	295	1.1	139	0	3467	5.1
179	37	295	2	23	2	295	1.1	139	0	3467	5.1

BDA software

y_{min}	M area + L area
274	38,380,647
179	38,399,489

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	20.1

DDY

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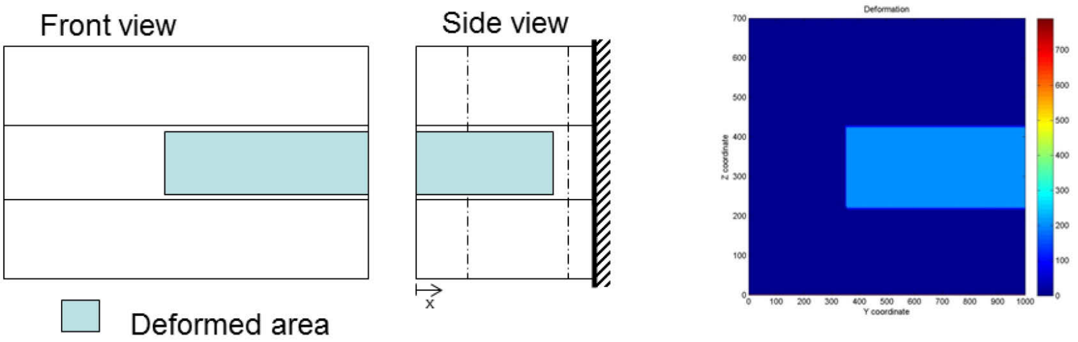
Department of Automotive Engineering

Profile 45



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	44	295	2	23	2	295	1.1	139	0	3774	5.1
179	44	295	2	23	2	295	1.1	139	0	3774	5.1

BDA software

y_{min}	M area + L area
274	52,808,370
179	52,834,295

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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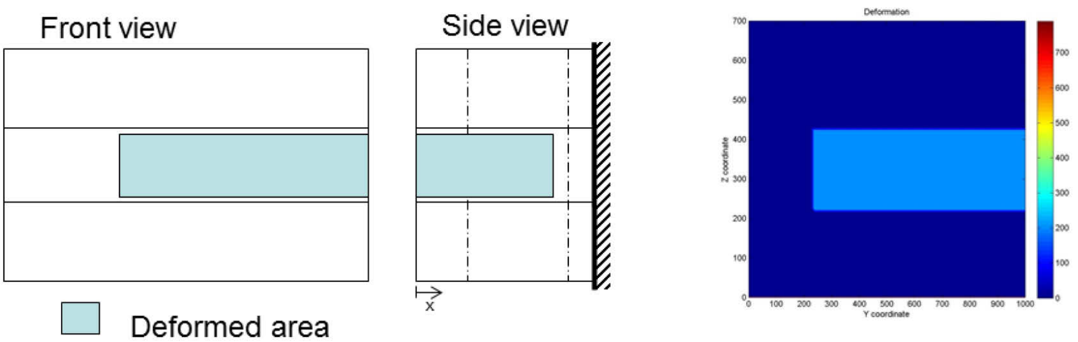
Profile 46



y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	52	295	2	23	2	295	1.1	139	0	3368	5.1
179	52	295	2	23	2	295	1.1	139	0	4070	5.1

BDA software

y_{min}	M area + L area
274	72,506,864
179	67,413,612

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

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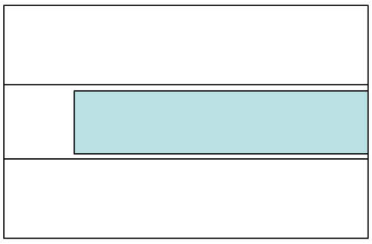
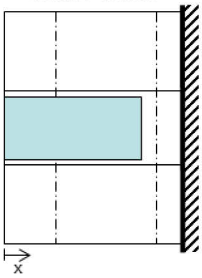
Profile 47

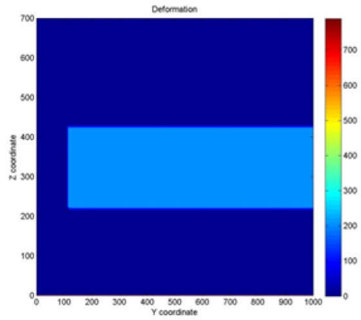
Front view



Deformed area

Side view





y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
274	59	295	2	23	2	295	1.1	139	0	3368	5.1
179	59	295	2	23	2	295	1.1	139	0	3635	5.1

BDA software

y_{min}	M area + L area
274	72,506,864
179	84,465,461

Homogeneity value

y_{min}	Row 3 + Row 4
274	0
179	0

DDY

Mathias Stein FIMCAR – WP 2 – Artificial PDB Profiles 50

Department of Automotive Engineering

PDB metric results

- **Summary of BDA assessment:**

profile	y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
1	274	24	295	2	23	2	295	1.1	139	0	5258	5.1
	179	24	295	2	23	2	295	1.1	139	0	5753	5.1
2	274	30	395	2	23	2	395	1.1	139	0	5264	5.1
	179	30	395	2	23	2	395	1.1	139	0	5680	5.1
3	274	51	395	2	23	2	395	2	295	0	5260	6
	179	51	395	2	23	2	395	2	395	0	5755	6
4	274	57	395	2	23	2	395	2	395	0	5240	6
	179	57	395	2	23	2	395	2	395	0	5735	6
5	274	51	495	2	23	0.9	495	1.6	195	0	5241	4.5
	179	51	495	2	23	0.9	495	1.6	195	0	5735	4.5
6	274	57	495	2	23	0.9	495	2	295	0	5261	4.9
	179	57	495	2	23	0.9	495	2	295	0	5756	4.9
7	274	71	495	2	23	0.9	495	1.5	495	0	5241	4.5
	179	71	495	2	23	0.9	495	1.5	495	0	5737	4.5
8	274	7	295	2	23	2	295	1.1	139	0	3738	5.1
	179	7	295	2	23	2	295	1.1	139	0	4109	5.1
9	274	7	395	2	23	2	395	1.1	139	0.3	2951	5.4
	179	7	395	2	23	2	395	1.1	139	0	4108	5.1
10	274	20	295	2	23	2	295	1.6	195	0.3	2950	5.9
	179	20	295	2	23	2	295	1.6	195	0	4106	5.6

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PDB metric results

- **Summary of BDA assessment:**

profile	y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
11	274	26	295	2	23	2	295	2	295	0.3	2950	6.3
	179	26	295	2	23	2	295	2	295	0	4106	6
12	274	21	395	2	23	2	395	1.6	195	0.3	2951	5.9
	179	21	395	2	23	2	395	1.6	195	0	4108	5.6
13	274	27	395	2	23	2	395	2	295	0.3	2951	6.3
	179	27	395	2	23	2	395	2	295	0	4108	6
14	274	34	395	2	23	2	395	2	395	0.3	2951	6.3
	179	34	395	2	23	2	395	2	395	0	4108	6
15	274	26	295	2	23	2	295	1.6	195	0	5258	5.6
	179	26	295	2	23	2	295	1.6	195	0	5753	5.6
16	274	26	295	2	23	2	295	2	295	0	5258	6
	179	26	295	2	23	2	295	2	295	0	5753	6
17	274	32	395	2	23	2	395	1.6	195	0	5264	5.6
	179	32	395	2	23	2	395	1.6	195	0	5680	5.6
18	274	33	395	2	23	2	395	2	295	0	5260	6
	179	33	395	2	23	2	395	2	295	0	5755	6
19	274	34	395	2	23	2	395	2	395	0	5260	6
	179	34	395	2	23	2	395	2	395	0	5755	6
20	274	44	395	2	23	1.6	195	2	395	0	5254	5.6
	179	44	395	2	23	1.6	195	2	395	0	5748	5.6

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PDB metric results

- **Summary of BDA assessment:**

profile	y_{min}	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
21	274	51	395	2	23	2	295	2	395	0	5258	6
	179	51	395	2	23	2	295	2	395	0	5753	6
22	274	44	295	2	23	2	295	2	295	0.7	2527	6.7
	179	44	295	2	23	2	295	2	295	0.3	2979	6.3
23	274	58	395	2	23	2	395	2	395	0.7	2528	6.7
	179	58	395	2	23	2	395	2	395	0.3	2980	6.3
24	274	44	295	2	23	2	295	1.1	139	0	3648	5.1
	179	44	295	2	23	2	295	1.1	139	0	4269	5.1
25	274	44	295	1.8	295	2	295	1.1	139	0.9	2286	5.7
	179	44	295	1.8	195	2	295	1.1	139	0.5	2761	5.3
26	274	57	295	2	23	2	295	1.1	139	0.5	2730	5.6
	179	57	295	2	23	2	295	1.1	139	0	3418	5.1
27	274	71	395	2	23	2	395	1.1	139	0.1	3208	5.2
	179	71	395	2	23	2	395	1.1	139	0	3892	5.1
28	274	57	395	0.1	395	2	395	1.1	139	0.9	2287	4.1
	179	57	395	0.1	395	2	395	1.1	139	0.5	2762	3.7
29	274	75	395	2	23	2	395	1.1	139	0.5	2731	5.6
	179	75	395	2	23	2	395	1.1	139	0	3419	5.1
30	274	24	295	2	23	2	295	2	295	0	3571	6
	179	24	295	2	23	2	295	2	295	0	3936	6

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PDB metric results

- **Summary of BDA assessment:**

profile	y_{mm}	volume [l]	max def [mm]	U area		M area		L area		H (M area)		PPS
				score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
21	274	21	295	2	23	2	295	2	295	0	5560	6
	179	21	295	2	23	2	295	2	295	0	5984	6
22	274	35	295	1.8	295	2	295	2	295	1.8	1297	7.5
	179	35	295	1.8	295	2	295	2	295	0.8	2406	6.5
23	274	85	295	1.8	295	2	295	2	295	1.3	1866	7
	179	85	295	1.8	295	2	295	2	295	0.5	2690	6.3
24	274	24	138	1.8	295	0	0	1.1	139	2	0	4.9
	179	24	138	1.8	295	0	0	1.1	139	2	0	4.9
25	274	31	184	0.1	395	0	0	1.1	139	2	0	3.2
	179	31	184	0.1	395	0	0	1.1	139	2	0	3.2
26	274	37	195	1.8	295	1.6	195	1.1	139	0	5254	4.4
	179	37	195	1.8	295	1.6	195	1.1	139	0	5748	4.4
27	274	44	295	1.8	295	2	295	1.1	139	0	5258	4.9
	179	44	295	1.8	295	2	295	1.1	139	0	5740	4.9
28	274	44	195	0.1	395	1.6	195	1.1	139	0	5254	2.8
	179	44	195	0.1	395	1.6	195	1.1	139	0	5748	2.8
29	274	60	295	1.8	295	2	295	2	295	0.5	2690	6.3
	179	60	295	1.8	295	2	295	2	295	0.5	2690	6.3
30	274	38	295	2	23	2	295	1.1	139	0	3506	5.1
	179	38	295	2	23	2	295	1.1	139	0	3506	5.1

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PDB metric results

- **Summary of BDA assessment:**

profile	y_{mm}	volume [l]	max def [mm]	U area		M area		L area		H (M area)		PPS
				score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
41	274	32	295	2	23	2	295	1.1	139	0	7485	5.1
	179	32	295	2	23	2	295	1.1	139	0	8076	5.1
42	274	22	295	2	23	2	295	1.1	139	0.4	2864	5.5
	179	22	295	2	23	2	295	1.1	139	0.4	2864	5.5
43	274	30	295	2	23	2	295	1.1	139	0.1	3153	5.2
	179	30	295	2	23	2	295	1.1	139	0.1	3153	5.2
44	274	37	295	2	23	2	295	1.1	139	0	3467	5.1
	179	37	295	2	23	2	295	1.1	139	0	3467	5.1
45	274	44	295	2	23	2	295	1.1	139	0	3774	5.1
	179	44	295	2	23	2	295	1.1	139	0	3774	5.1
46	274	52	295	2	23	2	295	1.1	139	0	3368	5.1
	179	52	295	2	23	2	295	1.1	139	0	4070	5.1
47	274	59	295	2	23	2	295	1.1	139	0	3368	5.1
	179	59	295	2	23	2	295	1.1	139	0	3635	5.1

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PDB metric results

- **Summary of Homogeneity value (TV upgraded) assessment:**

profile	y_{min}	M area + L area
1	274	13,784,463
	179	13,656,662
2	274	10,279,939
	179	9,916,783
3	274	23,747,366
	179	23,561,656
4	274	20,559,878
	179	20,366,140
5	274	8,196,167
	179	8,119,866
6	274	21,579,290
	179	21,352,871
7	274	16,392,335
	179	16,237,387
8	274	1,236,732
	179	1,237,340
9	274	725,859
	179	922,839
10	274	21,865,918
	179	20,952,283

profile	y_{min}	M area + L area
11	274	14,498,970
	179	14,433,905
12	274	25,464,133
	179	22,497,779
13	274	14,085,462
	179	13,736,080
14	274	10,812,289
	179	10,766,022
15	274	15,396,278
	179	15,724,373
16	274	14,501,685
	179	14,440,103
17	274	12,223,898
	179	11,890,413
18	274	11,315,870
	179	11,479,789
19	274	10,814,675
	179	10,768,078
20	274	29,508,035
	179	29,114,740

profile	y_{min}	M area + L area
21	274	23,674,984
	179	23,485,518
22	274	53,354,537
	179	49,439,924
23	274	39,789,825
	179	36,868,765
24	274	53,945,719
	179	49,987,650
25	274	43,076,448
	179	38,638,517
26	274	94,590,668
	179	84,020,634
27	274	62,034,281
	179	55,677,304
28	274	32,124,809
	179	28,814,103
29	274	70,542,193
	179	62,656,710
30	274	13,784,463
	179	13,656,623

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PDB metric results

- **Summary of Homogeneity value (TV upgraded) assessment:**

profile	y_{min}	M area + L area
31	274	9,142,383
	179	9,449,795
32	274	40,496,337
	179	32,291,821
33	274	76,604,559
	179	66,378,693
34	274	0
	179	0
35	274	0
	179	0
36	274	20,914,358
	179	20,722,533
37	274	14,085,754
	179	13,951,111
38	274	20,914,358
	179	20,722,533
39	274	20,914,358
	179	43,597,516
40	274	40,195,514
	179	40,215,247

profile	y_{min}	M area + L area
41	274	21,301,336
	179	21,714,007
42	274	10,764,362
	179	10,769,647
43	274	24,082,267
	179	24,094,090
44	274	38,380,647
	179	38,399,489
45	274	52,808,370
	179	52,834,295
46	274	72,506,864
	179	67,413,612
47	274	72,506,864
	179	84,465,461

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PDB metric results

- **Summary of DDY assessment:**

profile	y_{min}	Row 3 + Row 4
1	274	0
	179	0
2	274	0
	179	0
3	274	0
	179	0
4	274	0
	179	0
5	274	0
	179	0
6	274	0
	179	0
7	274	0
	179	0
8	274	0
	179	0
9	274	0
	179	0
10	274	0
	179	0

profile	y_{min}	Row 3 + Row 4
11	274	0
	179	0
12	274	0
	179	0
13	274	0
	179	0
14	274	0
	179	0
15	274	0
	179	0
16	274	0
	179	0
17	274	0
	179	0
18	274	0
	179	0
19	274	0
	179	0
20	274	0
	179	0

profile	y_{min}	Row 3 + Row 4
21	274	0
	179	0
22	274	0
	179	0
23	274	0
	179	0
24	274	0
	179	0
25	274	0
	179	0
26	274	0
	179	0
27	274	0
	179	0
28	274	0
	179	0
29	274	0
	179	0
30	274	0
	179	0

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PDB metric results

- **Summary of DDY assessment:**

profile	y_{min}	Row 3 + Row 4
31	274	0
	179	0
32	274	0
	179	0
33	274	20.1
	179	20.1
34	274	0
	179	0
35	274	0
	179	0
36	274	0
	179	0
37	274	0
	179	0
38	274	0
	179	0
39	274	20.1
	179	20.1
40	274	0
	179	20.1

profile	y_{min}	Row 3 + Row 4
41	274	20.1
	179	20.1
42	274	20.1
	179	20.1
43	274	20.1
	179	20.1
44	274	0
	179	20.1
45	274	0
	179	0
46	274	0
	179	0
47	274	0
	179	0

ANNEX G: PCM SIMULATION RESULTS

Department of Automotive Engineering

FIMCAR

PCM Simulations – PDB metric results

Department of Automotive Engineering

Request 3

- **Task:**
  - Sensitivity analysis of the PDB assessment criteria
- **Investigation:**
  - Influence of different parameters on assessment criteria
- **PCM Executive:**
  - vehicle width: 1878mm
  - vehicle mass: 1904kg

Mathias Stein FIMCAR – WP 2 – Request 3 2

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

PDB metric results

- **PDB assessment metrics**
  - **BDA software v1.0**
  - **Homogeneity value (TV upgraded)**
    - A_{def}(40%)
    - Assessment of middle and lower area ➔ z_{min} = 30mm & z_{max} = 450mm
  - **DDY**
    - 60% of vehicle width
    - Assessment area w.r.t. LCW Row 3 and Row 4 (330mm-580mm) ➔ z_{min} = 180mm & z_{max} = 430mm
    - 99%ile DDY

Mathias Stein *FIMCAR – WP 2 – Request 3* *3*

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Test Matrix

Comment	Priority	Parameter	Simulation run	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46*)	47*)
				Influence on vehicle mass					Influence on vehicle speed					Influence on crossbeam stiffness					Influence on crossbeam height					Influence on crossbeam length					Influence on subframe x-direction					Influence on subframe stiffness					Influence on subframe height					Influence on subframe length					bad compatibility expected	good compatibility expected
decrease of mass: engine mass - increase of mass: add masses to vehicle parts	3	[illegible]	given mass - 200 kg	x																																														
			given mass -100 kg		x																																													
			given mass			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
			given mass +100 kg				x																																											
			given mass + 200 kg					x																																										
	3	[illegible]	56 km/h						x																																									
			58 km/h							x																																								
			60 km/h	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
			61 km/h									x																																						
			64 km/h										x																																					
stiffness modification: bending stiffness ==> wall thickness	1	[illegible]	very weak: W=--> 0											x																																			x	
			weak: W=2												x																																			
			medium: W=	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
			stiff: W=*2														x																																	
			very stiff: W=*5															x																																x
	2	[illegible]	very low: z = 330 mm																x																															
			low: 410 mm																	x																														
			medium: z = 475 mm	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x
			high: z = 540 mm																			x																												
			very high: z = 600 mm																				x																										x	
	2	[illegible]	very short: no overlap																					x																									x	
			short: overlap = (vehicle width - longitudinal width) / 16																						x																									
			medium: overlap = (vehicle width - longitudinal width) / 8	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
			long: overlap = (vehicle width - longitudinal width) / 6																								x																							
			very long: overlap = (vehicle width - longitudinal width) / 4																									x																						x
	2	[illegible]	very rearward: x[illegible] + 300 mm																										x																				x	
			rearward: x[illegible] + 200 mm																											x																					
			medium: x[illegible] + 100 mm	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		
			forward: x[illegible]																													x																		
			very forward: x[illegible] - 100 mm																														x																	x
stiffness modification: bending stiffness ==> wall thickness	1	[illegible]	very weak: W=--> 0																															x															x	
			weak: W=2																																x															
			medium: W=	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x	x	x	x	x	x		
			stiff: W=*2																																		x													
			very stiff: W=*5																																			x												x
	2	[illegible]	very low: z = 180 mm																																				x											
			low: z = 220 mm																																					x										
			medium: z = 265 mm	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x			x	x	x	x	x		x
			high: z = 310 mm																																							x								
			very high: z = 350 mm																																								x						x	
	2	[illegible]	short: l = vehicle width * 40%																																									x					x	
			short: l = vehicle width * 55%																																										x					
			medium: l = vehicle width * 70%	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x				
			long: l = vehicle width * 85%																																												x			
			very long: l = vehicle width (wing width)																																													x		x

Test Matrix

- **Run 03 = basis model for parameters:**
  - Mass
  - Velocity
  - Cross beam stiffness
  - Cross beam height
  - Cross beam overlap

- **Run 33 = basis model for parameters:**
  - Sub frame x-direction
  - Sub frame stiffness
  - Sub frame height
  - Sub frame overlap

Influence of sub frame modifications in footprints were to low. So the basis model for the sub frame runs was adjusted.

Test Matrix

- **Vehicle mass:**
  - Parameters:
    - decreased mass - engine mass
    - Increased mass - cowl support and seat cross beam

    - Run 01: m_{engine} - 200kg
    - Run 02: m_{engine} - 100kg
    - Run 03: m_{engine} = 430kg / $m_{vehicle}$ = 1904kg (basis model)
    - Run 04: $m_{vehicle}$ + 100kg
    - Run 05: $m_{vehicle}$ + 200kg

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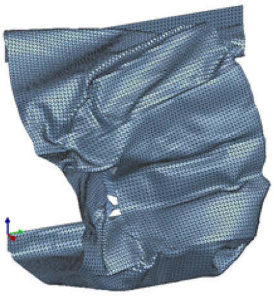
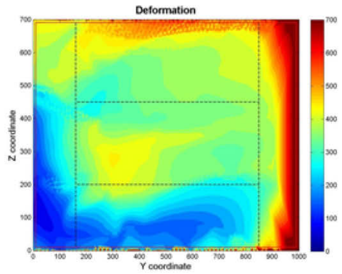
PDB metric results

- **Vehicle mass:**
  - Run 01





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
246	439	0	530	1.7	431	2	402	0	925	3.6

BDA software

M area + L area
240,907,448

Homogeneity value

Row 3 + Row 4
0.82

DDY

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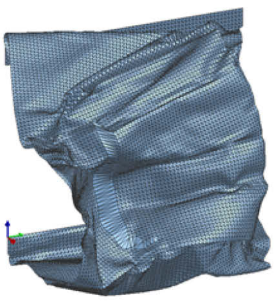
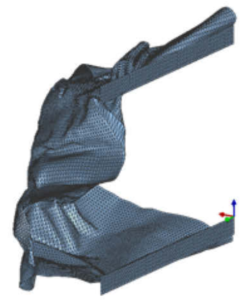
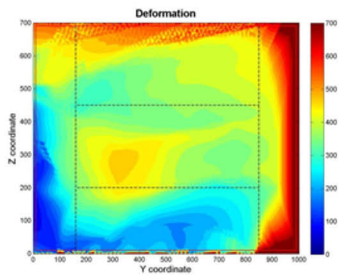
PDB metric results

- **Vehicle mass:**
  - Run 02

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
263	499	0	569	1.2	469	1.8	438	0	849	3

BDA software

M area + L area
258,625,071

Homogeneity value

Row 3 + Row 4
0.95

DDY

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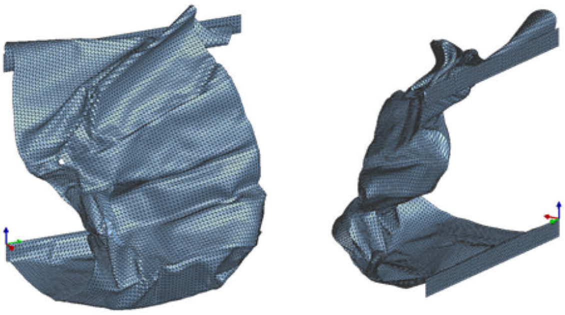
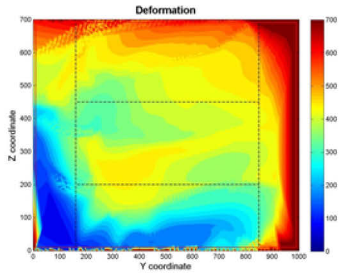
PDB metric results

- **Vehicle mass:**
  - Run 03 – basis model





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
247,266,229

Homogeneity value

Row 3 + Row 4
0.73

DDY

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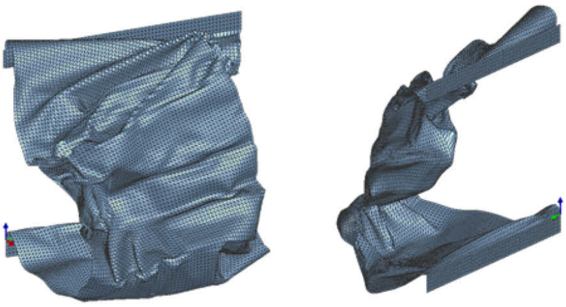
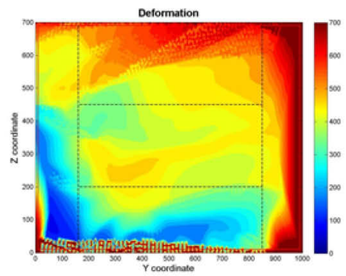
PDB metric results

- **Vehicle mass:**
  - Run 04





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
298	770	0	639	1.3	465	0.4	708	0	728	1.7

BDA software

M area + L area
152,111,517

Homogeneity value

Row 3 + Row 4
0.73

DDY

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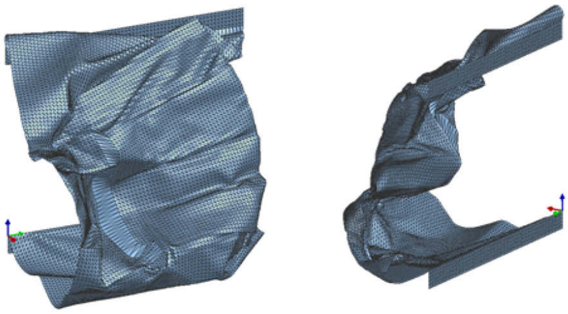
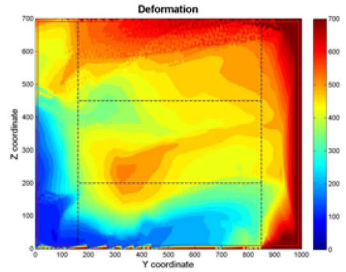
PDB metric results

- **Vehicle mass:**
  - Run 05





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
298	519	0	641	0.8	509	1.5	491	0	739	2.3

BDA software

M area + L area
226,780,112

Homogeneity value

Row 3 + Row 4
0.91

DDY

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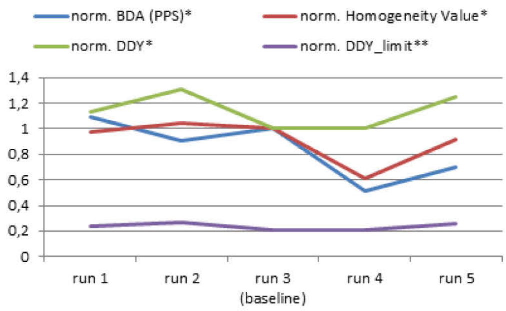
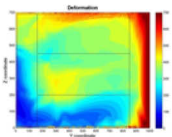
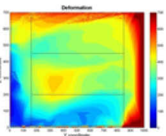
PDB metric results

- **Vehicle mass:**
  - Parameters:
    - decreased mass - engine mass
    - Increased mass - cowl support and seat cross beam
    - Run 01: m_{engine} - 200kg
    - Run 02: m_{engine} - 100kg
    - Run 03: m_{engine} = 430kg / $m_{vehicle}$ = 1904kg (basis model)
    - Run 04: $m_{vehicle}$ + 100kg
    - Run 05: $m_{vehicle}$ + 200kg

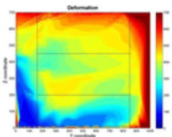




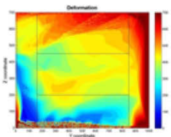
run 1



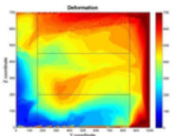
run 2



run 3 (baseline)



run 4



run 5

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Test Matrix

- **Vehicle speed:**
  - Parameter: initial velocity
    - Run 06: v = 56km/h
    - Run 07: v = 59km/h
    - Run 08: v = 60km/h (basis model)
    - Run 09: v = 61km/h
    - Run 10: v = 64km/h

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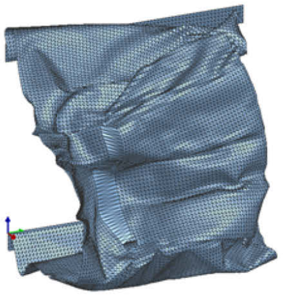
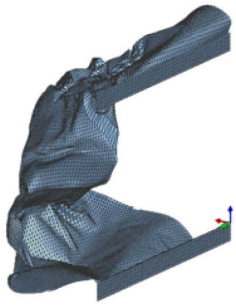
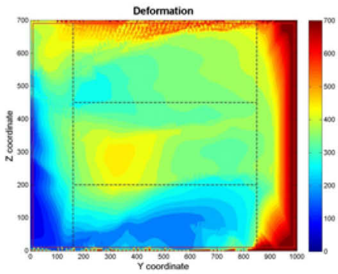
PDB metric results

- **Vehicle speed:**
  - Run 06







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
246	486	0	545	1.5	446	2	406	0	929	3.5

BDA software

M area + L area
253,560,389

Homogeneity value

Row 3 + Row 4
1.00

DDY

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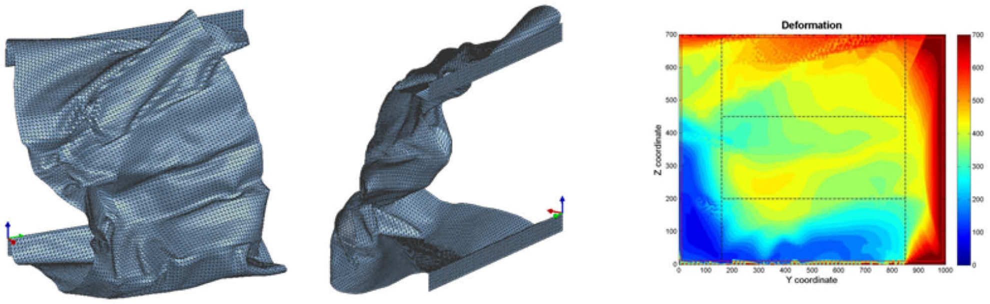
PDB metric results

- **Vehicle speed:**



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
267	452	0	583	1.6	439	1.9	417	0	778	3.5

BDA software

M area + L area
259,503,701

Homogeneity value

Row 3 + Row 4
0.70

DDY

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PDB metric results

- **Vehicle speed:**
  - Run 08 – basis model

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
247,266,229

Homogeneity value

Row 3 + Row 4
0.73

DDY

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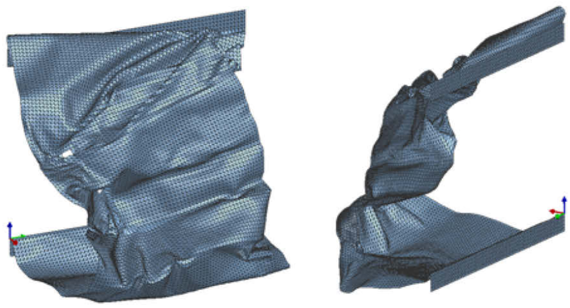
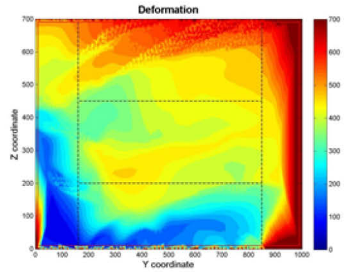
PDB metric results

- **Vehicle speed:**
  - Run 09





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
284	470	0	622	1.4	457	1.8	441	0	710	3.2

BDA software

M area + L area
243,904,964

Homogeneity value

Row 3 + Row 4
0.61

DDY

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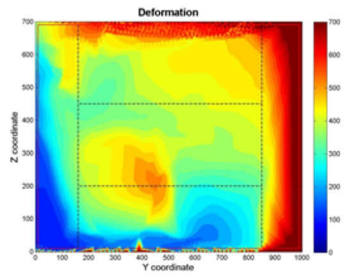
PDB metric results

- **Vehicle speed:**
  - Run 10



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
308	516	0	656	1	490	1.6	481	0	708	2.6

BDA software

M area + L area
229,121,681

Homogeneity value

Row 3 + Row 4
0.69

DDY

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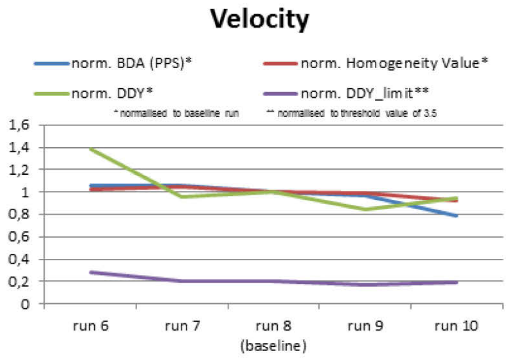
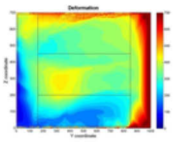
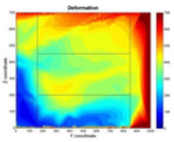
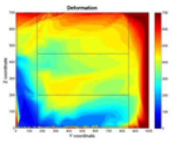
PDB metric results

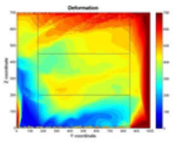
- **Vehicle speed:**
  - Parameter: initial velocity
    - Run 06: v = 56km/h
    - Run 07: v = 59km/h
    - Run 08: v = 60km/h (basis model)
    - Run 09: v = 61km/h
    - Run 10: v = 64km/h

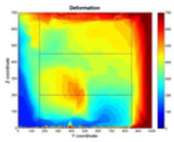



run 6


run 7


run 8 (baseline)


run 9


run 10

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Test Matrix

- **Cross beam stiffness:**
  - Parameter: wall thickness
    - Run 11_w/o cross beam
    - Run 11: t = 0.10mm
    - Run 12: t = 0.90mm
    - Run 13: t = 1.80mm (basis model)
    - Run 14: t = 3.54mm
    - Run 15: t = 10.00mm

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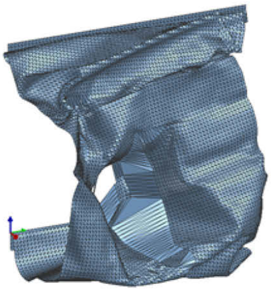
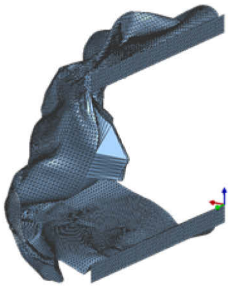
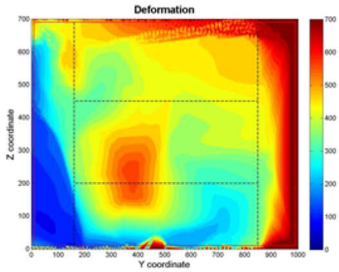
PDB metric results

- **Cross beam stiffness:**
  - Run 11 – w/o cross beam

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
277	579	0	601	0.2	565	1.2	556	0	855	1.4

BDA software

M area + L area
232,385,559

Homogeneity value

Row 3 + Row 4
2.60

DDY

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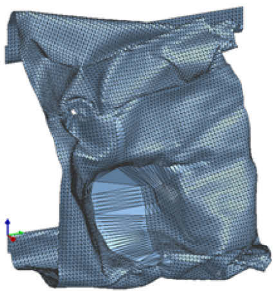
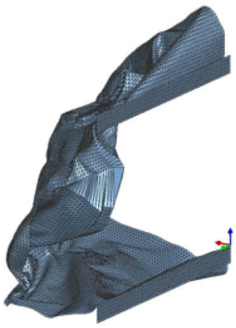
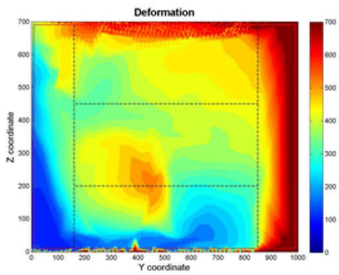
PDB metric results

- **Cross beam stiffness:**
  - Run 11

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
278	523	0	614	0.8	508	1.5	499	0	765	2.3

BDA software

M area + L area
251,624,569

Homogeneity value

Row 3 + Row 4
3.95

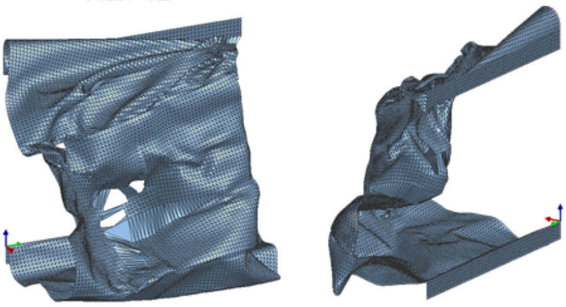
DDY

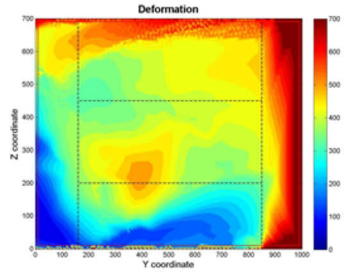
Mathias Stein FIMCAR – WP 2 – Request 3 22

Department of Automotive Engineering

PDB metric results

- **Cross beam stiffness:**
  - Run 12





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
277	500	0	589	1	493	1.6	481	0	689	2.6

BDA software

M area + L area
238,723,153

Homogeneity value

Row 3 + Row 4
1.32

DDY

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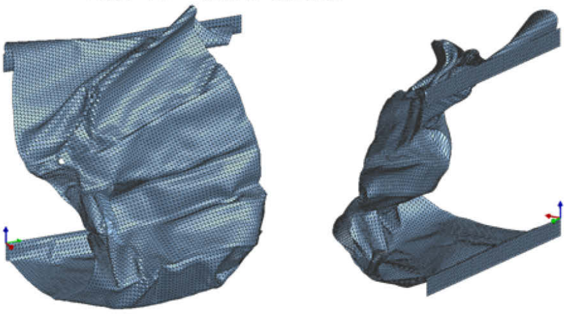
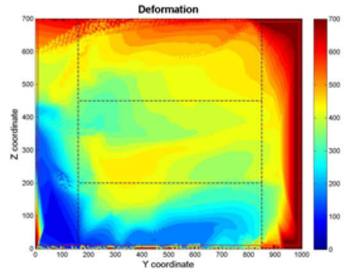
PDB metric results

- **Cross beam stiffness:**
  - Run 13 – basis model





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
247,266,229

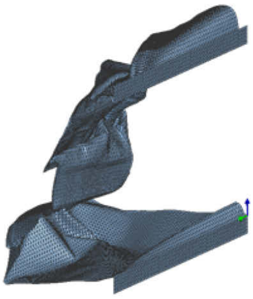
Homogeneity value

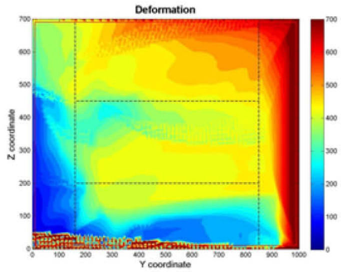
Row 3 + Row 4
0.73

DDY

PDB metric results

- **Cross beam stiffness:**
  - Run 14





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
280	744	0	576	1.6	439	0.4	708	0	1058	2

BDA software

M area + L area
186,052,136

Homogeneity value

Row 3 + Row 4
0.51

DDY

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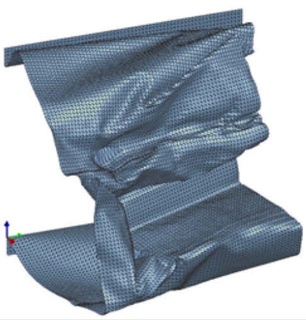
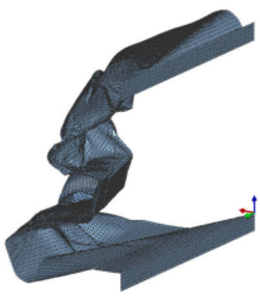
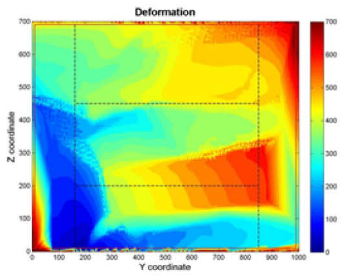
PDB metric results

- **Cross beam stiffness:**
  - Run 15







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
255	599	0	505	0	580	1.3	531	0	1673	1.3

BDA software

M area + L area
135,428,069

Homogeneity value

Row 3 + Row 4
1.49

DDY

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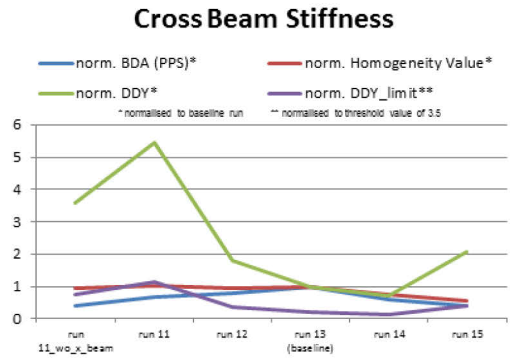
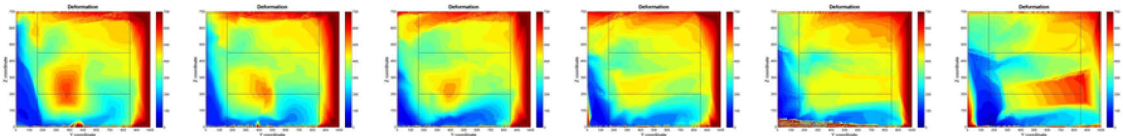
PDB metric results

- **Cross beam stiffness:**
  - Parameter: wall thickness
    - Run 11_w/o cross beam
    - Run 11: t = 0.10mm
    - Run 12: t = 0.90mm
    - Run 13: t = 1.80mm (basis model)
    - Run 14: t = 3.54mm
    - Run 15: t = 10.00mm





run 11 wo_x_beam | run 11 | run 12 | run 13 (baseline) | run 14 | run 15

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Test Matrix

- **Cross beam height:**
  - Parameter: distance from floor to middle point of cross section
    - Run 16: h = 350mm ➔ conflict with sub frame height in basis model
    - Run 17: h = 410mm
    - Run 18: h = 475mm (basis model)
    - Run 19: h = 540mm
    - Run 20: h = 600mm

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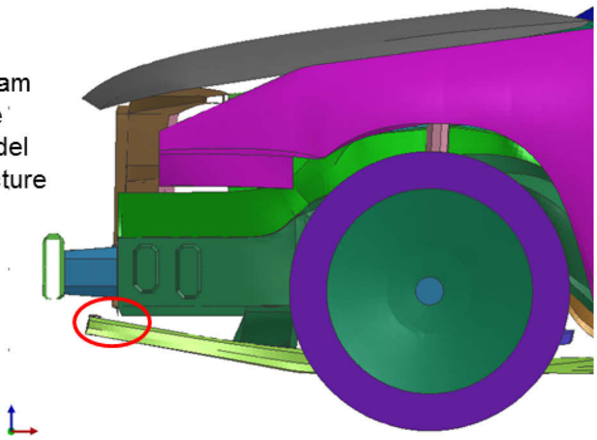
PDB metric results

- **Cross beam height:**
  - Run 16
  - Conflict:
    - Further reduction of cross beam height not possible due to the sub frame height in basis model
    - (picture shows height of structure of run 17)



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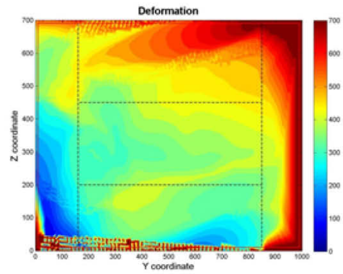
PDB metric results

- **Cross beam height :**
  - Run 17



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
286	771	0	652	1.6	435	0.6	682	0	708	2.2

BDA software

M area + L area
224,350,944

Homogeneity value

Row 3 + Row 4
0.53

DDY

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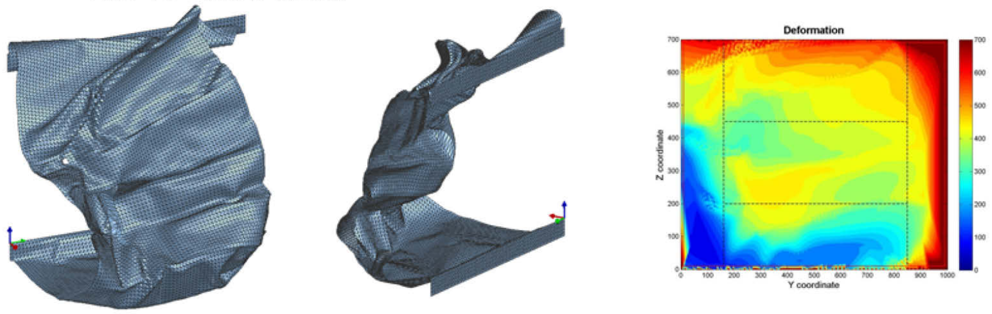
PDB metric results

- **Cross beam height :**
  - Run 18 – basis model



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
247,266,229

Homogeneity value

Row 3 + Row 4
0.73

DDY

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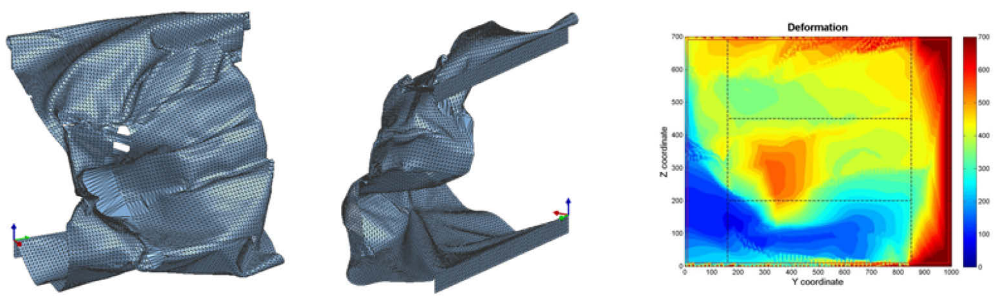
PDB metric results

- **Cross beam height :**
  - Run 19



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
264	553	0	569	0.4	543	1.6	471	0	1230	2

BDA software

M area + L area
145,861,158

Homogeneity value

Row 3 + Row 4
2.51

DDY

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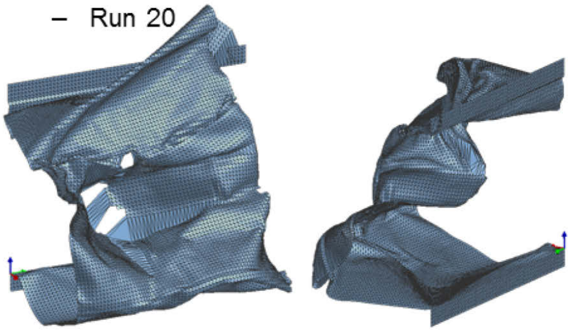
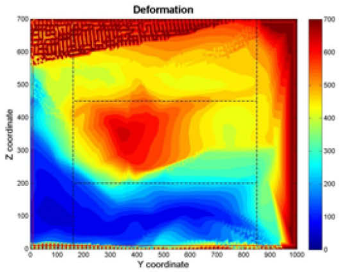
PDB metric results

- **Cross beam height :**
  - Run 20





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
278	640	0	761	0	629	2	362	0	1482	2

BDA software

M area + L area
100,553,580

Homogeneity value

Row 3 + Row 4
3.25

DDY

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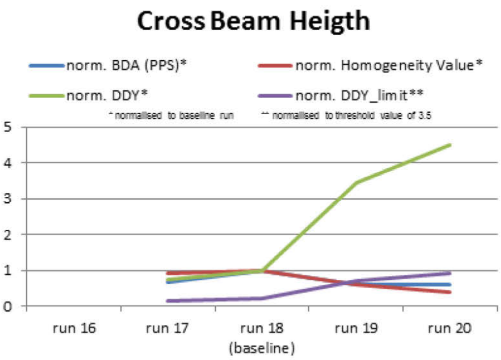
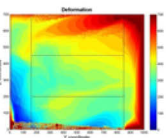
PDB metric results

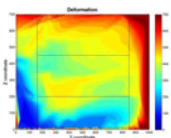
- **Cross beam height:**
  - Parameter: distance from floor to middle point of cross section
    - Run 16: h = 350mm ➔ conflict
    - Run 17: h = 410mm
    - Run 18: h = 475mm (basis model)
    - Run 19: h = 540mm
    - Run 20: h = 600mm



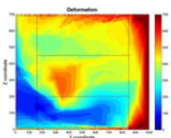
run 16



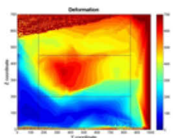
run 17



run 18 (baseline)



run 19



run 20

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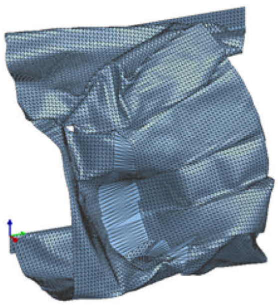
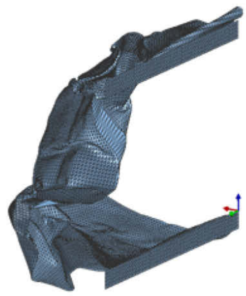
Test Matrix

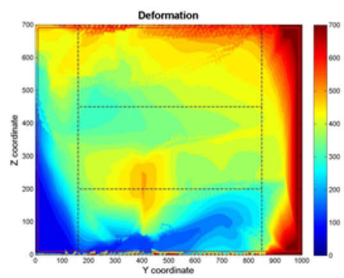
- **Cross beam width:**
  - Parameter: overlap (corresponds to half of vehicle width)
    - Run 21: very short (no overlap)
    - Run 22: short (vehicle width – longitudinal width)/16
    - Run 23: medium (vehicle width – longitudinal width)/8 (basis model)
    - Run 24: long (vehicle width – longitudinal width)/6
    - Run 25: very long (vehicle width – longitudinal width)/4

PDB metric results

- **Cross beam width:**
  - Run 21







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
263	487	0	560	1.1	477	1.6	476	0	796	2.8

BDA software

M area + L area
184,468,910

Homogeneity value

Row 3 + Row 4
1.18

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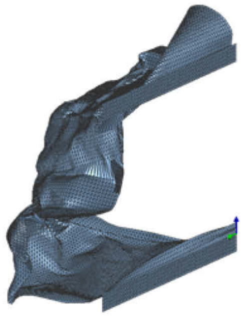
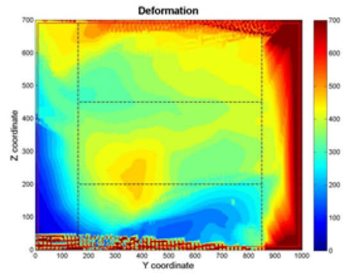
PDB metric results

- **Cross beam width:**
  - Run 22

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
272	772	0	574	1.2	469	0.3	732	0	734	1.5

BDA software

M area + L area
134,176,366

Homogeneity value

Row 3 + Row 4
1.11

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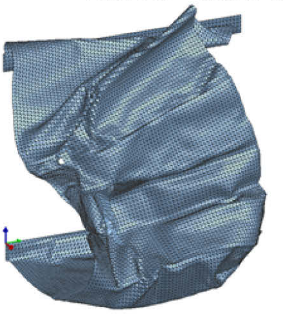
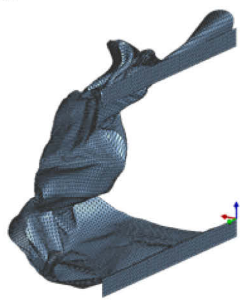
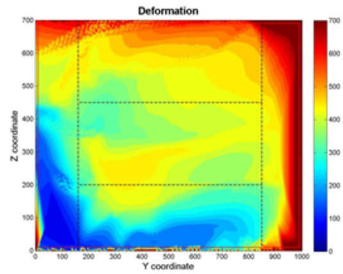
PDB metric results

- **Cross beam width:**
  - Run 23 – basis model

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
247,266,229

Homogeneity value

Row 3 + Row 4
0.73

DDY

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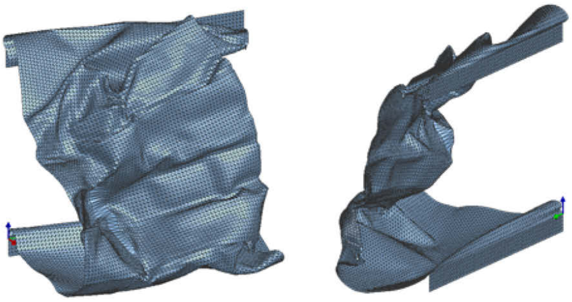
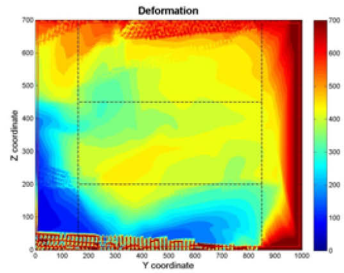
PDB metric results

- **Cross beam width:**
  - Run 24





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
284	768	0	617	1.5	442	0.3	731	0	670	1.8

BDA software

M area + L area
137,949,267

Homogeneity value

Row 3 + Row 4
0.84

DDY

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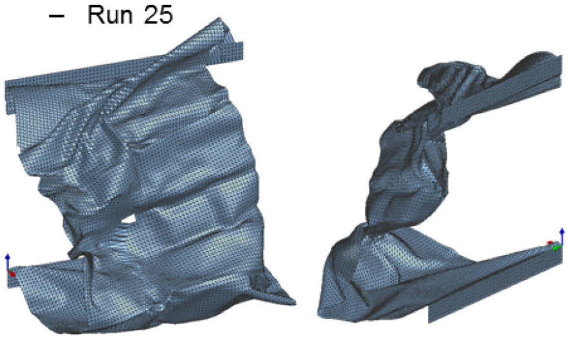
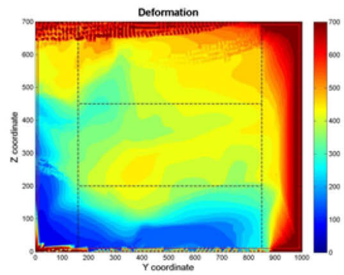
PDB metric results

- **Cross beam width:**
  - Run 25





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
279	469	0	737	1.5	441	1.9	422	0	611	3.4

BDA software

M area + L area
267,457,337

Homogeneity value

Row 3 + Row 4
0.66

DDY

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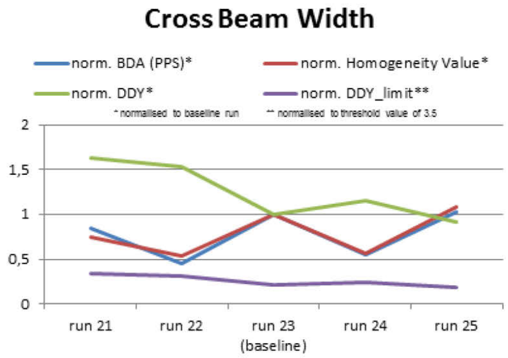
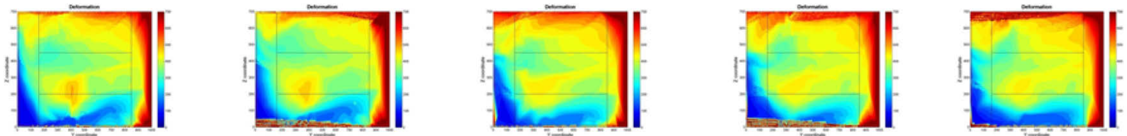
PDB metric results

- **Cross beam width:**
  - Parameter: overlap (corresponds to half of vehicle width)
    - Run 21: very short (no overlap)
    - Run 22: short (vehicle width – longitudinal width)/16
    - Run 23: medium (vehicle width – longitudinal width)/8 (basis model)
    - Run 24: long (vehicle width – longitudinal width)/6
    - Run 25: very long (vehicle width – longitudinal width)/4





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Test Matrix

- **Sub frame x-direction:**
  - Parameter: distance of cross beam and sub frame in x-direction
    - Run 26: very reward ($x_{cross\ beam}$ + 500mm)
    - Run 27: reward ($x_{cross\ beam}$ + 300mm)
    - Run 28: medium ($x_{cross\ beam}$ + 100mm)
    - Run 29: forward ($x_{cross\ beam}$)
    - Run 30: very forward ($x_{cross\ beam}$ - 100mm) ➔ conflict with bumper

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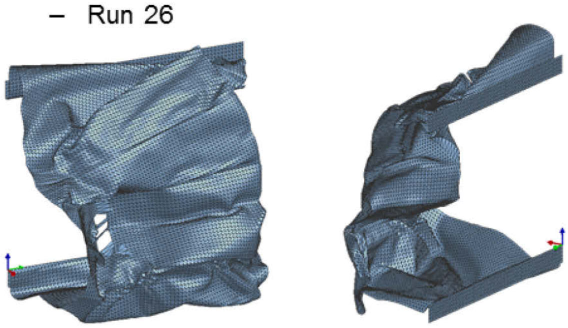
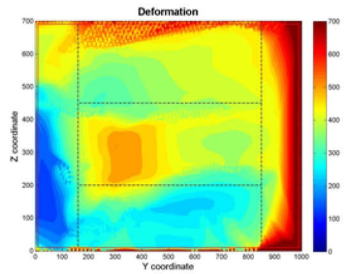
PDB metric results

- **Sub frame x-direction:**
  - Run 26





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
272	507	0	580	0.9	501	1.8	442	0	1101	2.7

BDA software

M area + L area
251,533,973

Homogeneity value

Row 3 + Row 4
1.30

DDY

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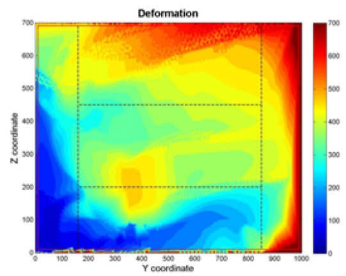
PDB metric results

- **Sub frame x-direction:**
  - Run 27



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
257	475	0	605	1.3	465	1.7	465	0	910	2.9

BDA software

M area + L area
209,567,010

Homogeneity value

Row 3 + Row 4
0.92

DDY

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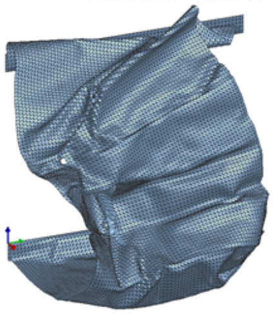
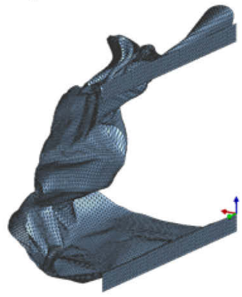
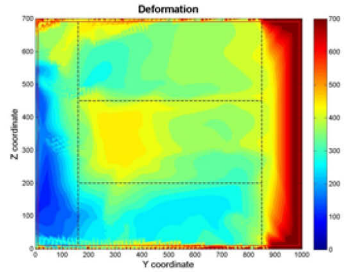
PDB metric results

- **Sub frame x-direction:**
  - Run 28 – basis model (reinforced sub frame)







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
276	493	0	582	1.4	452	1.8	432	0	806	3.3

BDA software

M area + L area
339,632,673

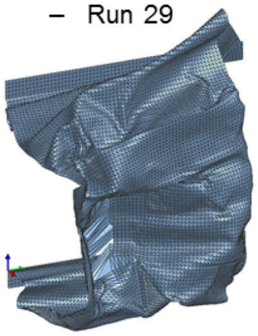
Homogeneity value

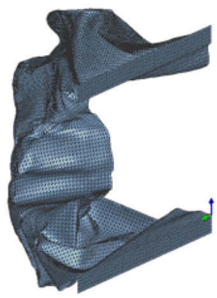
Row 3 + Row 4
1.73

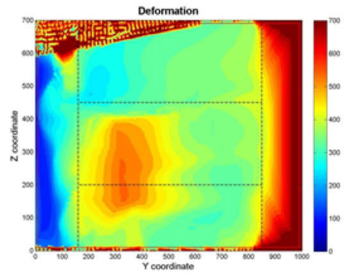
DDY

PDB metric results

- **Sub frame x-direction:**
  - Run 29







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
283	601	0	752	0.5	531	1.3	532	0	948	1.9

BDA software

M area + L area
289,406,184

Homogeneity value

Row 3 + Row 4
1.15

DDY

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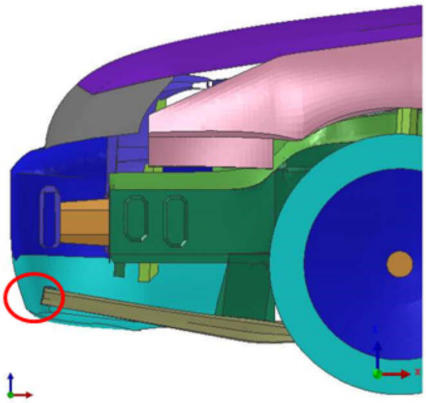
PDB metric results

- **Sub frame x-direction:**
  - Run 30
  - Conflict:
    - Further displacement of sub frame not possible due to the bumper in basis model
    - (picture shows sub frame and bumper of of run 29)



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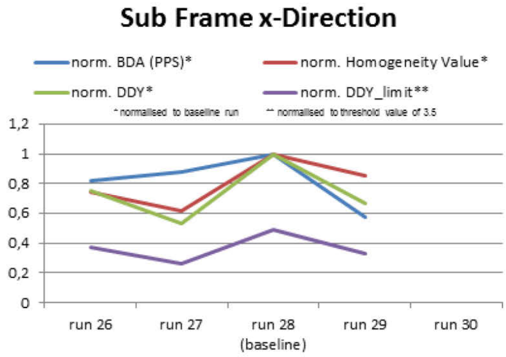
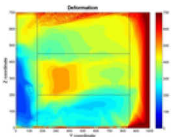
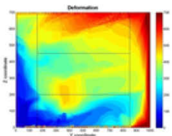
PDB metric results

- **Sub frame x-direction:**
  - Parameter: distance of cross beam and sub frame in x-direction
    - Run 26: very reward ($x_{cross\ beam}$ + 500mm)
    - Run 27: reward ($x_{cross\ beam}$ + 300mm)
    - Run 28: medium ($x_{cross\ beam}$ + 100mm)
    - Run 29: forward ($x_{cross\ beam}$)
    - Run 30: very forward ($x_{cross\ beam}$ - 100mm) ➔ conflict with bumper

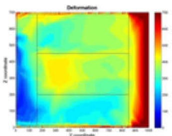




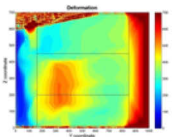
run 26



run 27



run 28 (baseline)



run 29

run 30

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Test Matrix

- **Sub frame stiffness:**
  - Parameter: wall thickness
    - Run 31: t = 0.10mm
    - Run 32: t = 1.00mm
    - Run 33: t = 2.00mm (basis model)
    - Run 34: t = 4.00mm
    - Run 35: t = 10.00mm

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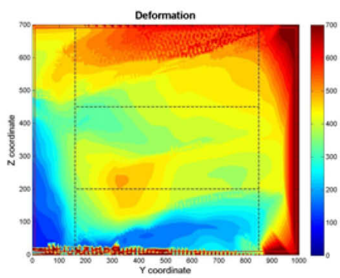
PDB metric results

- **Sub frame stiffness:**
  - Run 31



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
286	534	0	613	1.1	481	0.6	677	0	716	1.7

BDA software

M area + L area
231,924,454

Homogeneity value

Row 3 + Row 4
0.76

DDY

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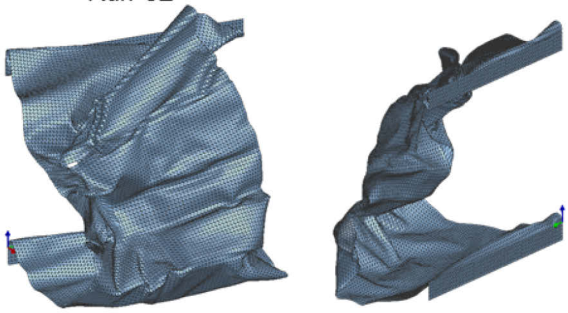
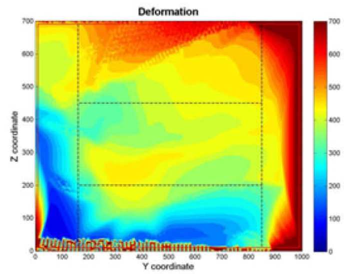
PDB metric results

- **Sub frame stiffness:**
  - Run 32





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
283	762	0	612	1.4	450	0.6	675	0	772	2

BDA software

M area + L area
194,267,834

Homogeneity value

Row 3 + Row 4
0.68

DDY

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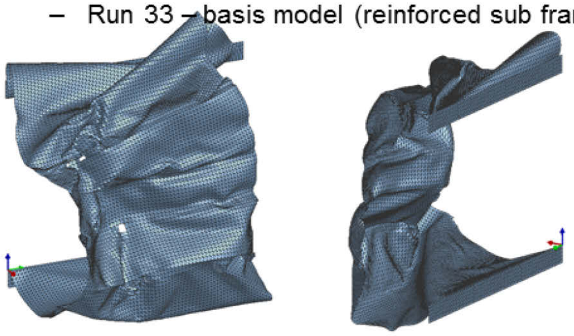
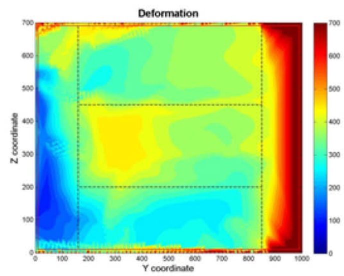
PDB metric results

- **Sub frame stiffness:**
  - Run 33 – basis model (reinforced sub frame)





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
258	452	0	451	1.4	451	1.8	436	0	798	3.3

BDA software

M area + L area
339,632,673

Homogeneity value

Row 3 + Row 4
1.73

DDY

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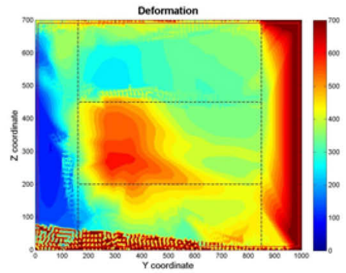
PDB metric results

- **Sub frame stiffness:**
  - Run 34



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
281	765	0	473	0	588	0.2	746	0	1037	0.2

BDA software

M area + L area
161,169,098

Homogeneity value

Row 3 + Row 4
1.24

DDY

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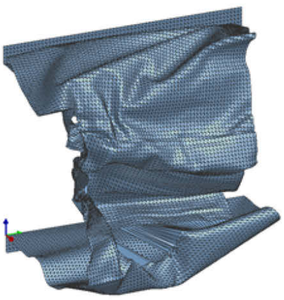
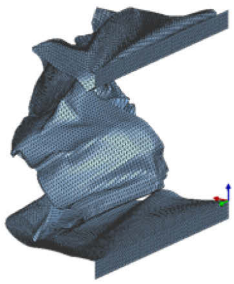
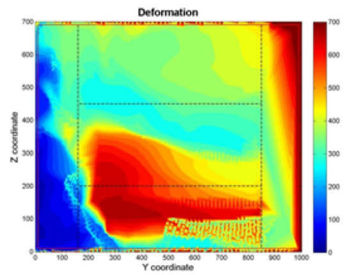
PDB metric results

- **Sub frame stiffness:**
  - Run 35







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
271	672	0	407	0	636	0.6	669	0	1540	0.6

BDA software

M area + L area
125,758,312

Homogeneity value

Row 3 + Row 4
2.52

DDY

Mathias Stein FIMCAR – WP 2 – Request 3 54

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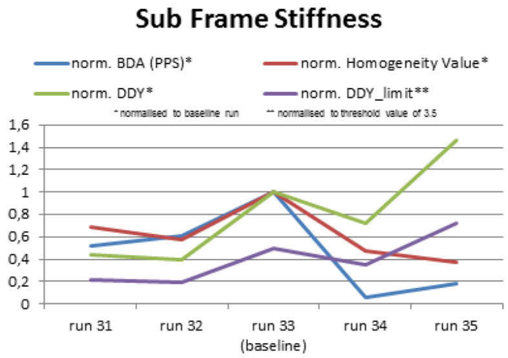
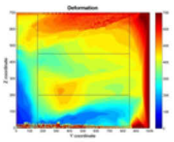
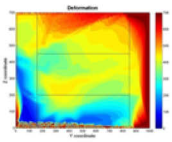
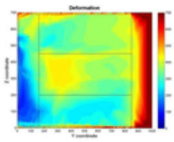
PDB metric results

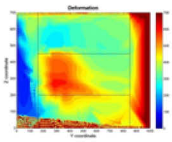
- **Sub frame stiffness:**
  - Parameter: wall thickness
    - Run 31: t = 0.10mm
    - Run 32: t = 1.00mm
    - Run 33: t = 2.00mm (basis model)
    - Run 34: t = 4.00mm
    - Run 35: t = 10.00mm

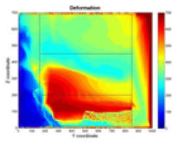



run 31


run 32


run 33 (baseline)


run 34


run 35

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Test Matrix

- **Sub frame height:**
  - Parameter: distance from floor to middle point of cross section
    - Run 36: h = 180mm
    - Run 37: h = 220mm
    - Run 38: h = 265mm (basis model)
    - Run 39: h = 310mm
    - Run 40: h = 350mm

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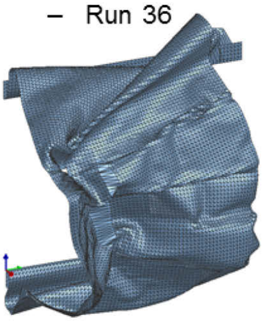
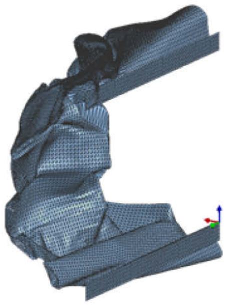
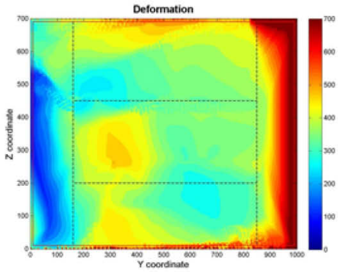
PDB metric results

- **Sub frame height:**
  - Run 36







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
263	516	0	492	1.2	471	1.6	487	0	1106	2.8

BDA software

M area + L area
301,731,271

Homogeneity value

Row 3 + Row 4
1.17

DDY

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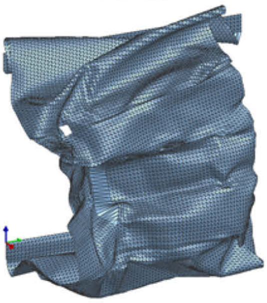
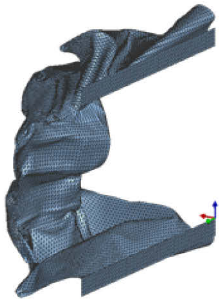
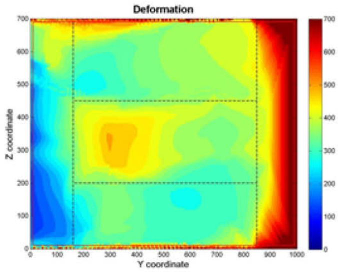
PDB metric results

- **Sub frame height:**
  - Run 37







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
266	519	0	498	1.1	479	1.9	413	0	918	3.1

BDA software

M area + L area
360,258,532

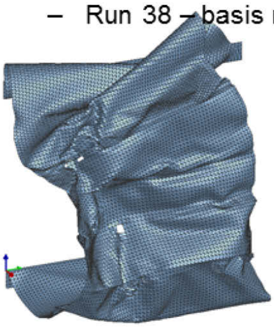
Homogeneity value

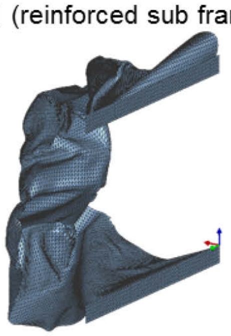
Row 3 + Row 4
0.95

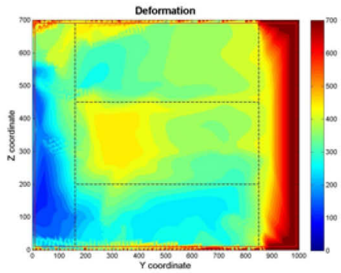
DDY

PDB metric results

- **Sub frame height:**
  - Run 38 – basis model (reinforced sub frame)







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
258	452	0	451	1.4	451	1.8	436	0	798	3.3

BDA software

M area + L area
339,632,673

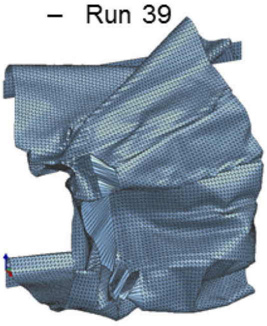
Homogeneity value

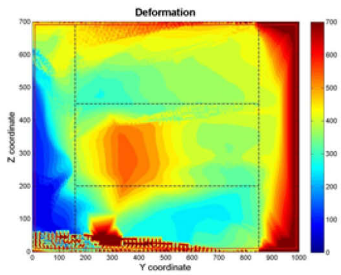
Row 3 + Row 4
1.73

DDY

PDB metric results

- **Sub frame height:**
  - Run 39





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
276	770	0	529	0.4	542	0.2	750	0	1175	0.6

BDA software

M area + L area
97,203,135

Homogeneity value

Row 3 + Row 4
1.14

DDY

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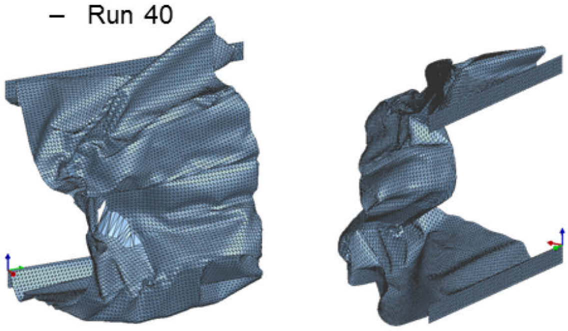
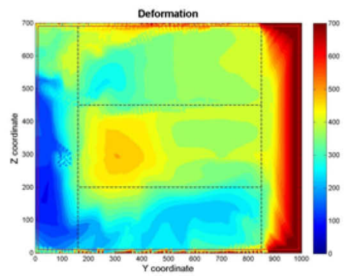
PDB metric results

- **Sub frame height:**
  - Run 40





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
255	484	0	483	1.1	477	1.9	413	0	904	3.1

BDA software

M area + L area
294,283,927

Homogeneity value

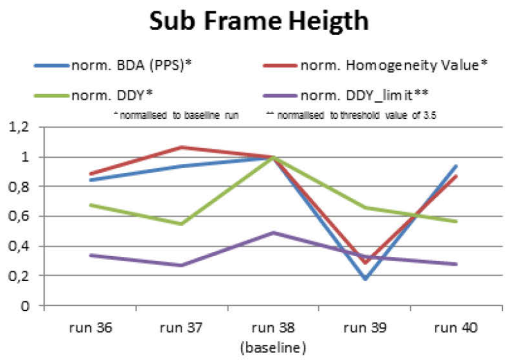
Row 3 + Row 4
0.97

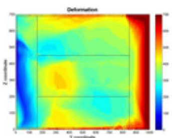
DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

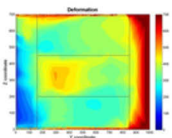
PDB metric results

- **Sub frame height:**
  - Parameter: distance from floor to middle point of cross section
    - Run 36: h = 180mm
    - Run 37: h = 220mm
    - Run 38: h = 265mm (basis model)
    - Run 39: h = 310mm
    - Run 40: h = 350mm

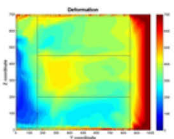




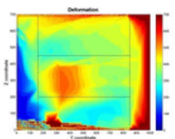
run 36



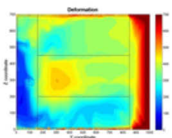
run 37



run 38 (baseline)



run 39



run 40

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Test Matrix

- **Sub frame width:**
  - Parameter: percentage of vehicle width
    - Run 41: vehicle width * 40%
    - Run 42: vehicle width * 55%
    - Run 43: vehicle width * 70% (basis model)
    - Run 44: vehicle width * 85%
    - Run 45: vehicle width * 100% (wing width) ➔ Conflict with shape of wings

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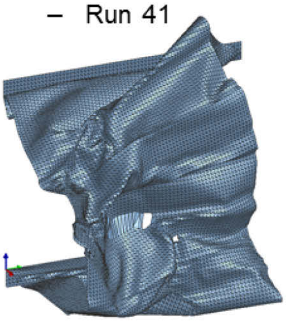
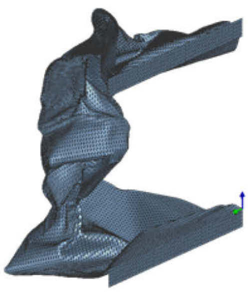
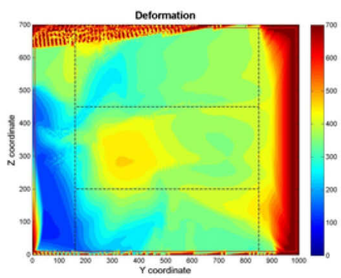
Department of Automotive Engineering

PDB metric results

- **Sub frame width:**
  - Run 41







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
263	463	0	677	1.4	456	2	407	0	928	3.3

BDA software

M area + L area
308,284,332

Homogeneity value

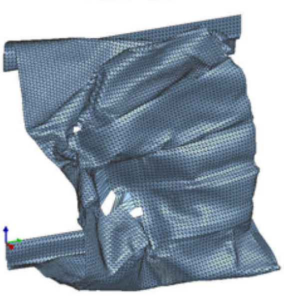
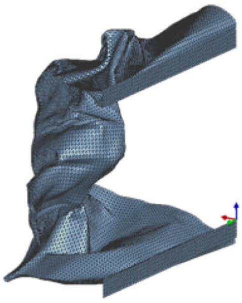
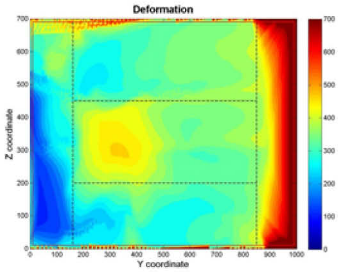
Row 3 + Row 4
1.38

DDY

Department of Automotive Engineering

PDB metric results

- **Sub frame width:**
  - Run 42

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
249	462	0	483	1.4	458	2	376	0	827	3.4

BDA software

M area + L area
362,116,103

Homogeneity value

Row 3 + Row 4
0.96

DDY

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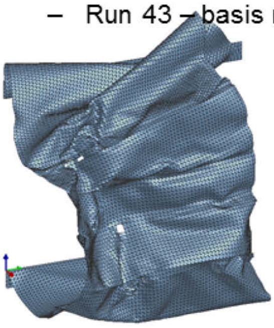
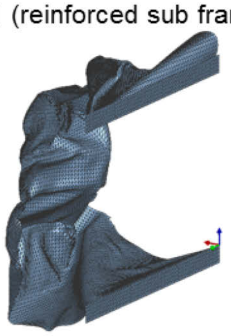
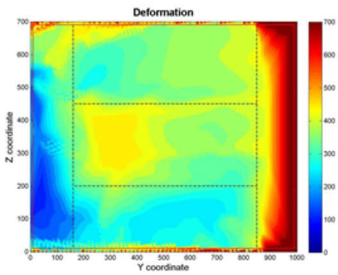
PDB metric results

- **Sub frame width:**
  - Run 43 – basis model (reinforced sub frame)

volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
258	452	0	451	1.4	451	1.8	436	0	798	3.3

BDA software

M area + L area
339,632,673

Homogeneity value

Row 3 + Row 4
1.73

DDY

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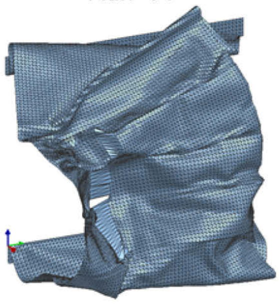
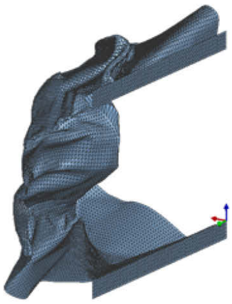
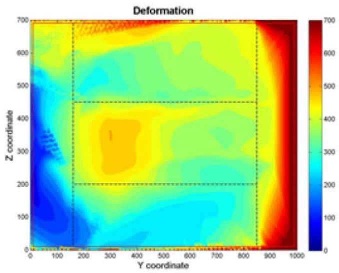
PDB metric results

- **Sub frame width:**
  - Run 44







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
260	484	0	530	1.1	478	1.9	415	0	840	3.1

BDA software

M area + L area
318,586,976

Homogeneity value

Row 3 + Row 4
1.21

DDY

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PDB metric results

- **Sub frame width:**
  - Run 45
  - Conflict:
    - Sub frame width of Run 44 was the maximum width which was possible to create

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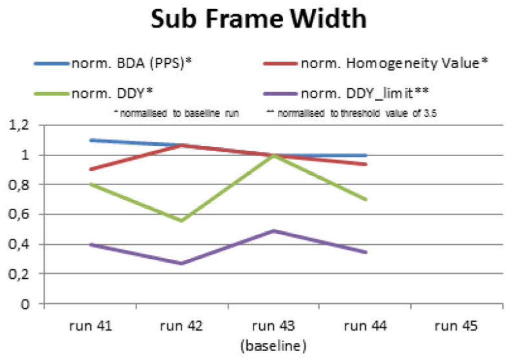
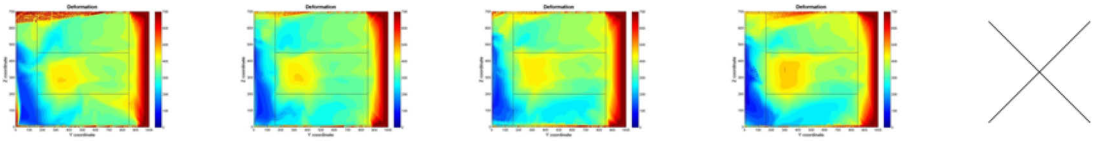
PDB metric results

- **Sub frame width:**
  - Parameter: percentage of vehicle width
    - Run 41: vehicle width * 40%
    - Run 42: vehicle width * 55%
    - Run 43: vehicle width * 70% (basis model)
    - Run 44: vehicle width * 85%
    - Run 45: vehicle width * 100% (wing width) ➔ Conflict with shape of wings





run 41 | run 42 | run 43 (baseline) | run 44 | run 45

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PDB metric results

- **Summary of BDA assessment:**

parameter	modification	run	volume [l]	max def [mm]	U area		M area		L area		H (M area)		PPS
					score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
mass (decrease of engine mass and increase of cowl support and seat cross beam mass)	- 200kg	1	246	439	0	530	1.7	431	2	402	0	925	3.6
	- 100kg	2	263	499	0	569	1.2	469	1.8	438	0	849	3
	= 430kg	3	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	+ 100kg	4	298	770	0	639	1.3	465	0.4	708	0	728	1.7
	+ 200kg	5	298	519	0	641	0.8	509	1.5	491	0	739	2.3
velocity	56km/h	6	246	486	0	545	1.5	446	2	406	0	929	3.5
	59km/h	7	267	452	0	583	1.6	439	1.9	417	0	778	3.5
	60km/h	8	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	61km/h	9	284	470	0	622	1.4	457	1.8	441	0	710	3.2
	64km/h	10	308	516	0	656	1	490	1.6	481	0	708	2.6
cross beam stiffness (wall thickness)		11_wo_x_beam	277	579	0	601	0.2	565	1.2	556	0	855	1.4
	0.10mm	11	278	523	0	614	0.8	508	1.5	499	0	765	2.3
	0.90mm	12	277	500	0	589	1	493	1.6	481	0	689	2.6
	1.80mm	13	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	3.54mm	14	280	744	0	576	1.6	439	0.4	708	0	1058	2
	10.0mm	15	255	599	0	505	0	580	1.3	531	0	1673	1.3
cross beam height (distance between floor and middle point of cross section)	350mm	16						-					
	410mm	17	286	771	0	652	1.6	435	0.6	682	0	708	2.2
	475mm	18	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	540mm	19	264	553	0	569	0.4	543	1.6	471	0	1230	2
	600mm	20	278	640	0	761	0	629	2	362	0	1482	2
cross beam width	very short	21	263	487	0	560	1.1	477	1.6	476	0	796	2.8
	short	22	272	772	0	574	1.2	469	0.3	732	0	734	1.5
	medium	23	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	long	24	284	768	0	617	1.5	442	0.3	731	0	670	1.8
	very long	25	279	469	0	737	1.5	441	1.9	422	0	611	3.4

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PDB metric results

- **Summary of BDA assessment:**

parameter	modification	run	volume [l]	max def [mm]	U area		M area		L area		H (M area)		PPS
					score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
sub frame x-direction (measured from cross beam)	+ 500mm	26	272	507	0	580	0.9	501	1.8	442	0	1101	2.7
	+ 300mm	27	257	475	0	605	1.3	465	1.7	465	0	910	2.9
	+ 100mm	28	276	493	0	582	1.4	452	1.8	432	0	806	3.3
	0mm	29	283	601	0	752	0.5	531	1.3	532	0	948	1.9
	-100mm	30						-					
sub frame stiffness (wall thickness)	0.10mm	31	286	534	0	613	1.1	481	0.6	677	0	716	1.7
	1.00mm	32	283	762	0	612	1.4	450	0.6	675	0	772	2
	2.00mm	33	258	452	0	451	1.4	451	1.8	436	0	798	3.3
	4.00mm	34	281	765	0	473	0	588	0.2	746	0	1037	0.2
	10.0mm	35	271	672	0	407	0	636	0.6	669	0	1540	0.6
sub frame height (distance between floor and middle point of cross section)	180mm	36	263	516	0	492	1.2	471	1.6	487	0	1106	2.8
	220mm	37	266	519	0	498	1.1	479	1.9	413	0	918	3.1
	265mm	38	258	452	0	451	1.4	451	1.8	436	0	798	3.3
	310mm	39	276	770	0	529	0.4	542	0.2	750	0	1175	0.6
	350mm	40	255	484	0	483	1.1	477	1.9	413	0	904	3.1
sub frame width	very short	41	249	462	0	483	1.4	458	2	376	0	827	3.4
	short	42	258	452	0	451	1.4	451	1.8	436	0	798	3.3
	medium	43	260	484	0	530	1.1	478	1.9	415	0	840	3.1
	long	44	260	484	0	530	1.1	478	1.9	415	0	840	3.1
	very long	45						-					

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PDB metric results

- **Summary of Homogeneity value (TV upgraded) assessment:**

parameter	modification	run	M area + L area
mass (decrease of engine mass and increase of cowl support and seat cross beam mass)	- 200kg	1	240,907,448
	- 100kg	2	258,625,071
	= 430kg	3	247,266,229
	+ 100kg	4	152,111,517
	+ 200kg	5	226,780,112
velocity	56km/h	6	253,560,389
	59km/h	7	259,503,701
	60km/h	8	247,266,229
	61km/h	9	243,904,964
	64km/h	10	229,121,681
cross beam stiffness (wall thickness)		11_wo_x_beam	232,385,559
	0.10mm	11	251,624,569
	0.90mm	12	238,723,153
	1.80mm	13	247,266,229
	3.54mm	14	186,052,136
	10.0mm	15	135,428,069
cross beam height (distance between floor and middle point of cross section)	---	16	-
	410mm	17	224,350,944
	475mm	18	247,266,229
	540mm	19	145,861,158
	600mm	20	100,553,580
cross beam width	very short	21	184,468,910
	short	22	134,176,366
	medium	23	247,266,229
	long	24	137,949,267
	very long	25	267,457,337

parameter	modification	run	M area + L area
sub frame x-direction (measured from cross beam)	+ 500mm	26	251,533,973
	+ 300mm	27	209,567,010
	+ 100mm	28	339,632,673
	0mm	29	289,406,184
	- 100mm	30	-
sub frame stiffness (wall thickness)	0.10mm	31	231,924,454
	1.00mm	32	194,267,834
	2.00mm	33	339,632,673
	4.00mm	34	161,169,098
	10.0mm	35	125,758,312
sub frame height (distance between floor and middle point of cross section)	180mm	36	301,731,271
	220mm	37	360,258,532
	265mm	38	339,632,673
	310mm	39	97,203,135
	350mm	40	294,283,927
sub frame width	very short	41	308,284,332
	short	42	362,116,103
	medium	43	339,632,673
	long	44	318,586,976
	very long	45	-

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PDB metric results

- **Summary of DDY metric assessment:**

parameter	modification	run	Row 3 + Row 4
mass (decrease of engine mass and increase of cowl support and seat cross beam mass)	- 200kg	1	0.82
	- 100kg	2	0.95
	= 430kg	3	0.73
	+ 100kg	4	0.73
	+ 200kg	5	0.91
velocity	56km/h	6	1.00
	59km/h	7	0.70
	60km/h	8	0.73
	61km/h	9	0.61
	64km/h	10	0.69
cross beam stiffness (wall thickness)		11_wo_x_beam	2.60
	0.10mm	11	3.95
	0.90mm	12	1.32
	1.80mm	13	0.73
	3.54mm	14	0.51
	10.0mm	15	1.49
cross beam height (distance between floor and middle point of cross section)	---	16	-
	410mm	17	0.53
	475mm	18	0.73
	540mm	19	2.51
	600mm	20	3.25
cross beam width	very short	21	1.18
	short	22	1.11
	medium	23	0.73
	long	24	0.84
	very long	25	0.66

parameter	modification	run	Row 3 + Row 4
sub frame x-direction (measured from cross beam)	+ 500mm	26	1.30
	+ 300mm	27	0.92
	+ 100mm	28	1.73
	0mm	29	1.15
	- 100mm	30	-
sub frame stiffness (wall thickness)	0.10mm	31	0.76
	1.00mm	32	0.68
	2.00mm	33	1.73
	4.00mm	34	1.24
	10.0mm	35	2.52
sub frame height (distance between floor and middle point of cross section)	180mm	36	1.17
	220mm	37	0.95
	265mm	38	1.73
	310mm	39	1.14
	350mm	40	0.97
sub frame width	very short	41	1.38
	short	42	0.96
	medium	43	1.73
	long	44	1.21
	very long	45	-

ANNEX H: GCM SIMULATION RESULTS

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FIMCAR

GCM Simulations – PDB metric results

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GCMs – PDB metric results

- **Overview of the different GCMs:**

GCM	Vehicle Class	Lower Load Path available	Vehicle Width [mm]
GCM_1_A	Super Mini	no	1720
GCM_1_B		yes	
GCM_2_A	Small Family Car	yes	1822
GCM_2_B		no	
GCM_3_A	Large Executive	yes	1828

Mathias Stein FIMCAR – WP 2 – GCM vs. PDB 2

Department of Automotive Engineering

GCMs – PDB metric results

- **PDB assessment metrics**
  - **BDA software v1.0**
  - **Homogeneity value (TV upgraded)**
    - $A_{def}(40\%)$
    - Assessment of middle and lower area ➔ z_{min} = 30mm & z_{max} = 450mm
  - **DDY**
    - 60% of vehicle width
    - Assessment area w.r.t. LCW Row 3 and Row 4 (330mm-580mm)
      ➔ z_{min} = 180mm & z_{max} = 430mm
    - 99%ile DDY

Mathias Stein FIMCAR – WP 2 – GCM vs. PDB 3

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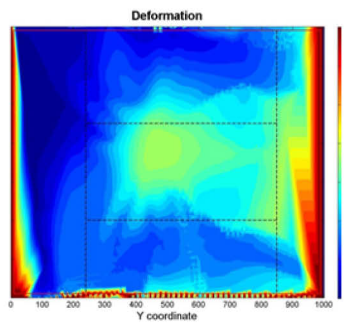
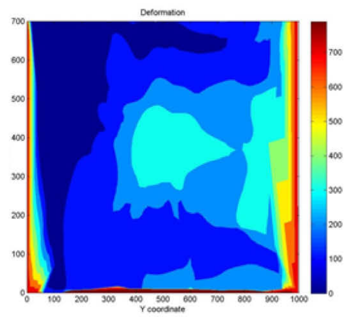
GCMs – PDB metric results

- **GCM_1_A:**





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
156	379	1.3	323	2	376	1.3	529	0	1503	4.6

BDA software

M area + L area
185,244,384

Homogeneity value

Row 3 + Row 4
3.9

DDY

Mathias Stein FIMCAR – WP 2 – GCM vs. PDB 4

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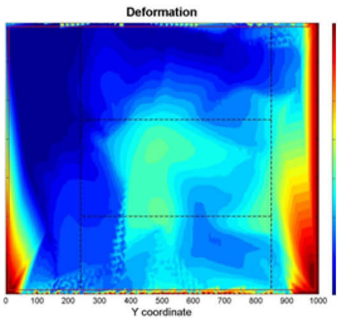
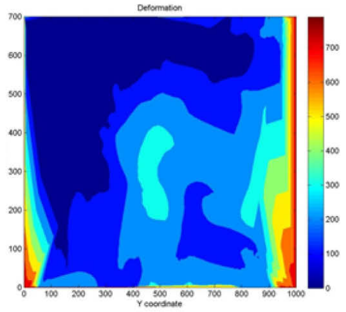
GCMs – PDB metric results

- **GCM_1_B:**





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
137	379	1.3	342	2	319	2	319	1.4	1699	7.4

BDA software

M area + L area
186,229,164

Homogeneity value

Row 3 + Row 4
1.9

DDY

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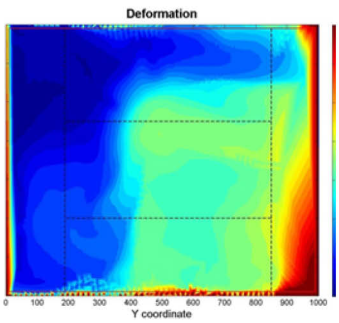
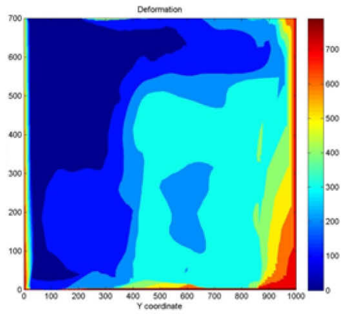
GCMs – PDB metric results

- **GCM_2_A:**





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
169	407	1	341	2	379	1.6	472	1.9	1106	6.5

BDA software

M area + L area
274,581,139

Homogeneity value

Row 3 + Row 4
1.1

DDY

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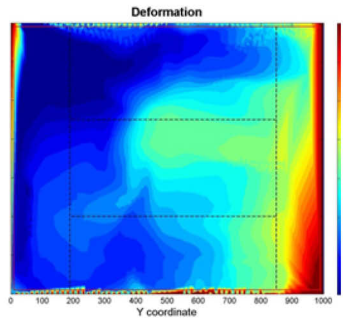
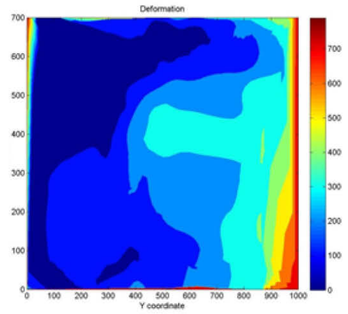
GCMs – PDB metric results

- **GCM_2_B:**





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
149	405	1.6	307	2	336	2	319	1.7	1357	7.3

BDA software

M area + L area
220,354,041

Homogeneity value

Row 3 + Row 4
1.5

DDY

Mathias Stein FIMCAR – WP 2 – GCM vs. PDB 7

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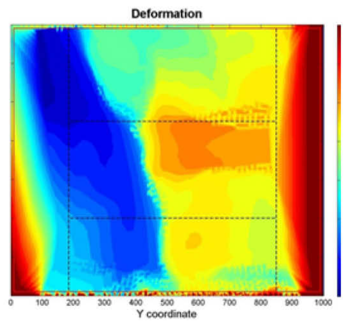
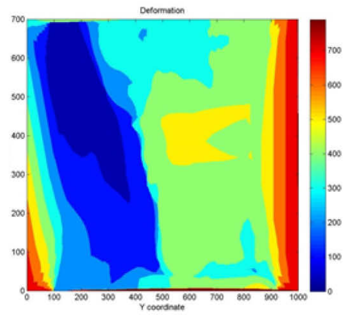
GCMs – PDB metric results

- **GCM_3_A:**





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
251	524	0	495	0.7	520	1.7	457	0	1304	2.4

BDA software

M area + L area
124,239,703

Homogeneity value

Row 3 + Row 4
5.1

DDY

Mathias Stein FIMCAR – WP 2 – GCM vs. PDB 8

GCMs – PDB metric results

- **Summary of BDA assessment:**

GCM	volume [l]	max def [mm]	U area		M area		L area		H (M area)		PPS
			score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
GCM_1_A	156	379	1.3	323	2	376	1.3	529	0	1503	4.6
GCM_1_B	137	379	1.3	342	2	319	2	319	1.4	1699	7.4
GCM_2_A	169	407	1	341	2	379	1.6	472	1.9	1106	6.5
GCM_2_B	149	405	1.6	307	2	336	2	319	1.7	1357	7.3
GCM_3_A	251	524	0	495	0.7	520	1.7	457	0	1304	2.4

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GCMs – PDB metric results

- **Summary of Homogeneity value (TV upgraded) assessment:**

GCM	M area + L area
GCM_1_A	185,244,384
GCM_1_B	186,229,164
GCM_2_A	274,581,139
GCM_2_B	220,354,041
GCM_3_A	124,239,703

GCMs – PDB metric results

- **Summary of DDY metric assessment:**

GCM	Row 3 + Row 4
GCM_1_A	3.9
GCM_1_B	1.9
GCM_2_A	1.1
GCM_2_B	1.5
GCM_3_A	5.1

ANNEX I: TEST PDB PROFILES

frontal impact and compatibility assessment research

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FIMCAR

Vehicle PDB Profiles

frontal impact and compatibility assessment research

frontal impact and compatibility assessment research

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- **PDB assessment metrics**
  - **BDA software v1.0**
  - **Homogeneity value (TV upgraded)**
    - $A_{def}(40\%)$
    - Assessment of middle and lower area ➔ z_{min} = 30mm & z_{max} = 450mm
  - **DDY**
    - 60% of vehicle width
    - Assessment area w.r.t. LCW Row 3 and Row 4 (330mm-580mm) ➔ z_{min} = 180mm & z_{max} = 430mm
    - 99%ile DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 2

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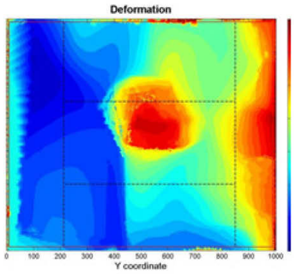
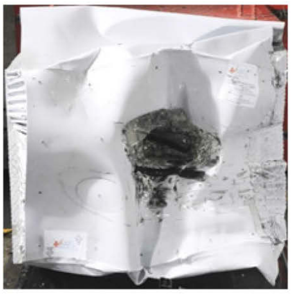
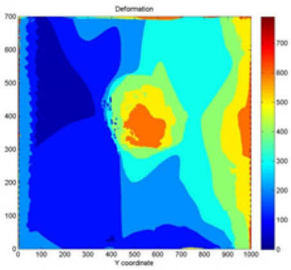
- vehicle: FIMCAR_SFC_1
- vehicle width: 1775mm
- group: G3
- barrier depth: 790mm
- driver position: LHD







volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
200	646	0	545	0	638	2	304	1.2	1966	3.2

BDA software

M area + L area
47,915,147

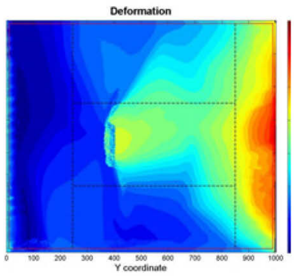
Homogeneity value

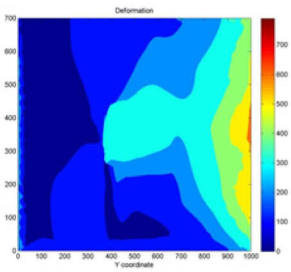
Row 3 + Row 4
7.1

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: FIMCAR_Supermini_1_UTAC
- vehicle width: 1708mm
- group: G3
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
146	415	1.3	321	2	402	2	246	1.3	1826	6.6

BDA software

M area + L area
100,495,224

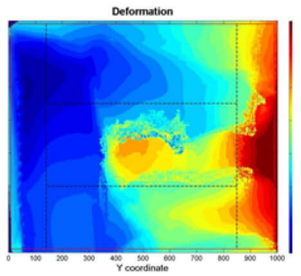
Homogeneity value

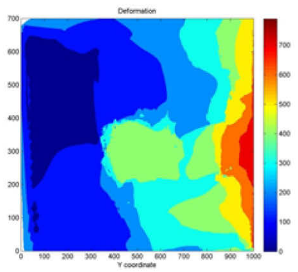
Row 3 + Row 4
1.4

DDY

Department of Automotive Engineering

- vehicle: 56_SUV_4_without_ACE
- vehicle width: 1920mm
- group: G3
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
185	579	1.3	320	0.8	504	1.8	431	0	3390	4

BDA software

M area + L area
65,332,503

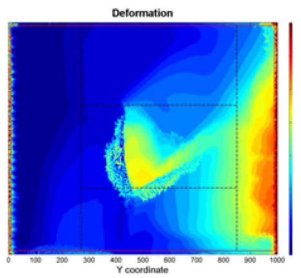
Homogeneity value

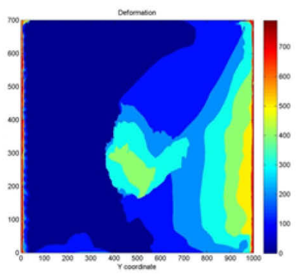
Row 3 + Row 4
17.3

DDY

Department of Automotive Engineering

- vehicle: 52_Supermini_6
- barrier depth: 790mm
- driver position: LHD
- vehicle width: 1660mm
- group: G3





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
116	451	2	169	1.6	437	2	341	0	3819	5.6

BDA software

M area + L area
62,144,259

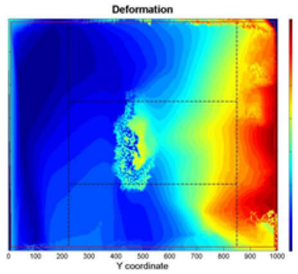
Homogeneity value

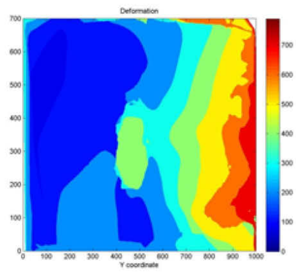
Row 3 + Row 4
10.0

DDY

Department of Automotive Engineering

- vehicle: 37_Small_SUV
- vehicle width: 1815mm
- group: G3
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
157	570	1	339	1	489	1.8	430	0.1	3131	4

BDA software

M area + L area
71,464,524

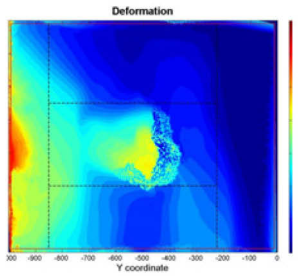
Homogeneity value

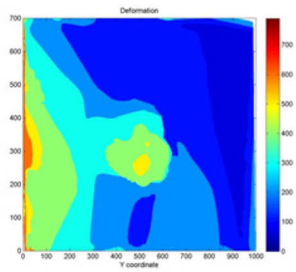
Row 3 + Row 4
8.6

DDY

Department of Automotive Engineering

- vehicle: 19_Supermini_5_DAD
- vehicle width: 1752mm
- group: G3
- barrier depth: 700mm
- driver position: RHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
110	433	2	170	1.8	419	2	265	0	3626	5.8

BDA software

M area + L area
85,738,397

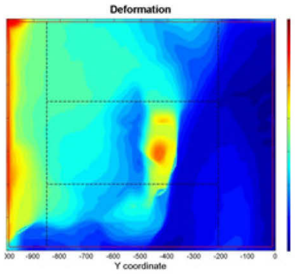
Homogeneity value

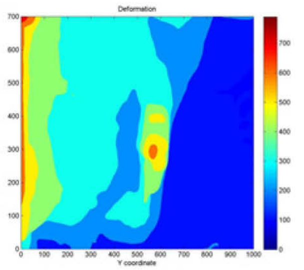
Row 3 + Row 4
3.0

DDY

Department of Automotive Engineering

- vehicle: 17_SUV_7
- vehicle width: 1778mm
- group: G3
- barrier depth: 700mm
- driver position: RHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
137	537	1.6	303	0.9	500	2	358	0.7	2444	5.2

BDA software

M area + L area
74,689,634

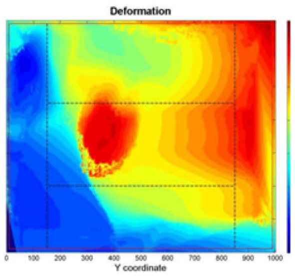
Homogeneity value

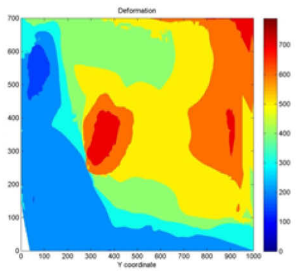
Row 3 + Row 4
6.6

DDY

Department of Automotive Engineering

- vehicle: 11_SUV_6
- vehicle width: 1898mm
- group: G3
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
252	629	0	509	0	624	1.8	431	0	1459	1.8

BDA software

M area + L area
129,748,335

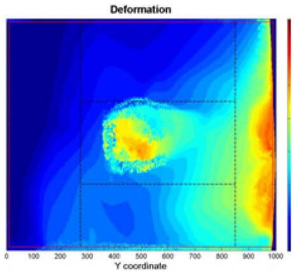
Homogeneity value

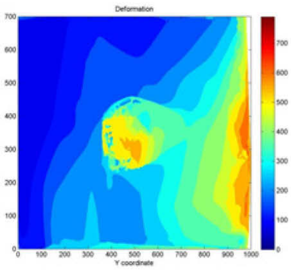
Row 3 + Row 4
3.9

DDY

Department of Automotive Engineering

- vehicle: 09_Supermini_5_DAG
- vehicle width: 1649mm
- group: G3
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
117	502	2	184	1.2	474	2	300	0	3433	5.2

BDA software

M area + L area
47,775,587

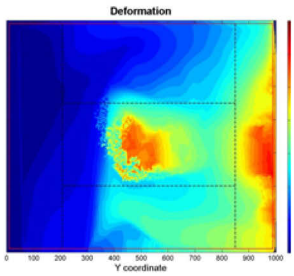
Homogeneity value

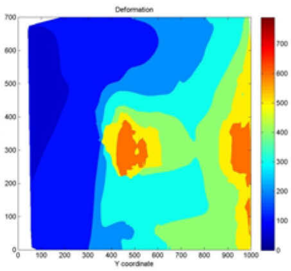
Row 3 + Row 4
5.3

DDY

Department of Automotive Engineering

- vehicle: 05_SFC_2_weak
- vehicle width: 1783mm
- group: G3
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
138	558	2	252	0.5	534	2	336	0.1	3160	4.6

BDA software

M area + L area
108,672,228

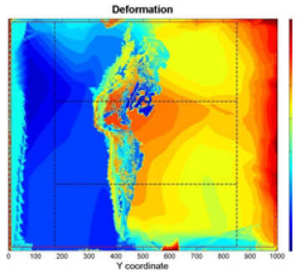
Homogeneity value

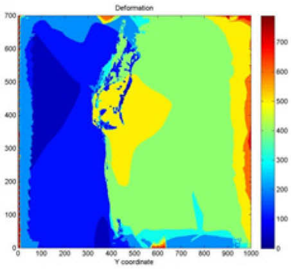
Row 3 + Row 4
6.3

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: FIMCAR_SUV_1_IDIADA
- vehicle width: 1855mm
- group: G2
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
228	582	0	548	0.1	568	1.5	495	0	3792	1.6

BDA software

M area + L area
59,929,260

Homogeneity value

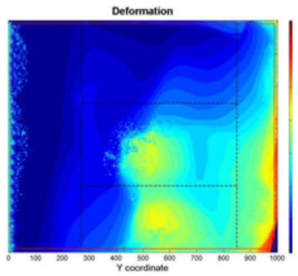
Row 3 + Row 4
0.8

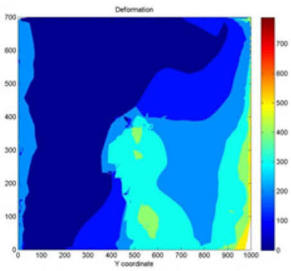
DDY

Mathias Stein   FIMCAR – WP 2 – Vehicle PDB Profiles   13

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: FIMCAR_City_Car_1_UTAC
- vehicle width: 1655mm
- group: G2
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
104	425	2	153	2	390	1.9	417	0.8	2373	6.7

BDA software

M area + L area
81,782,461

Homogeneity value

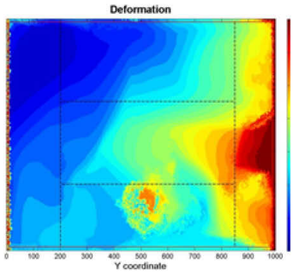
Row 3 + Row 4
7.4

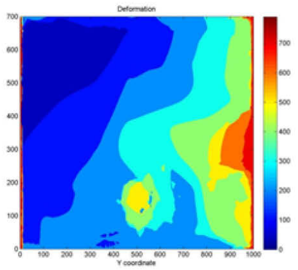
DDY

Mathias Stein   FIMCAR – WP 2 – Vehicle PDB Profiles   14

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 53_Family_car
- vehicle width: 1798mm
- group: G2
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
189	589	1.6	302	0.7	518	1.4	513	1.7	1364	5.4

BDA software

M area + L area
82,156,892

Homogeneity value

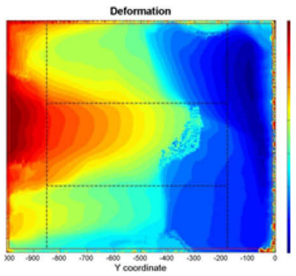
Row 3 + Row 4
5.4

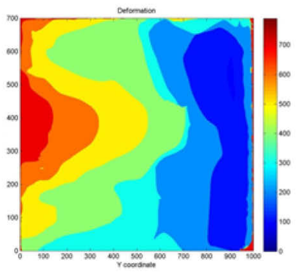
DDY

Mathias Stein — FIMCAR – WP 2 – Vehicle PDB Profiles — 15

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 48_SUV_5
- vehicle width: 1845mm
- group: G2
- barrier depth: 700mm
- driver position: RHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
212	591	0	477	0	577	2	367	0	1438	2

BDA software

M area + L area
189,619,514

Homogeneity value

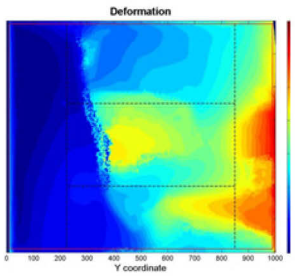
Row 3 + Row 4
1.5

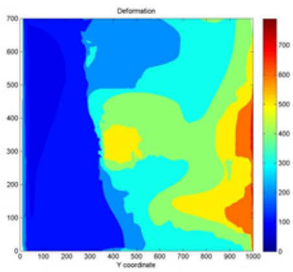
DDY

Mathias Stein — FIMCAR – WP 2 – Vehicle PDB Profiles — 16

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 35_SFC_3_repeat
- vehicle width: 1751mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
154	488	1.1	333	1.7	431	1.8	435	1	2207	5.5

BDA software

M area + L area
127,369,304

Homogeneity value

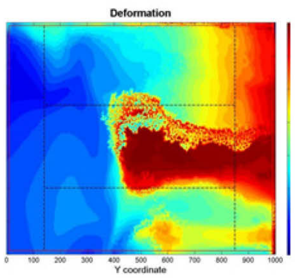
Row 3 + Row 4
2.0

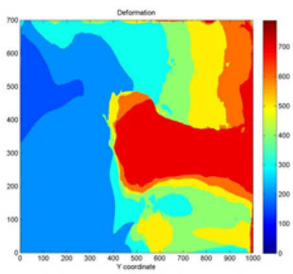
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 17

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 30_SUV_4
- vehicle width: 1920mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
231	694	0	511	0	692	1.4	496	0	3599	1.4

BDA software

M area + L area
57,173,388

Homogeneity value

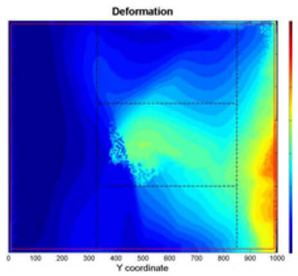
Row 3 + Row 4
15.7

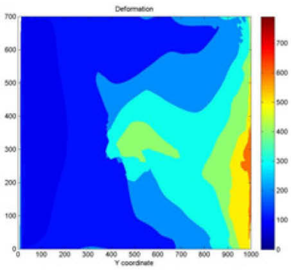
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 18

Department of Automotive Engineering

- vehicle: 28_Supermini_4
- vehicle width: 1540mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume	max def	U area		M area		L area		H (M area)		PPS
[l]	[mm]	score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
99	344	2	218	2	339	2	258	1	2135	7

BDA software

M area + L area
131,503,576

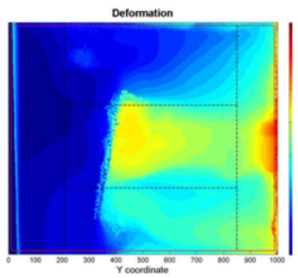
Homogeneity value

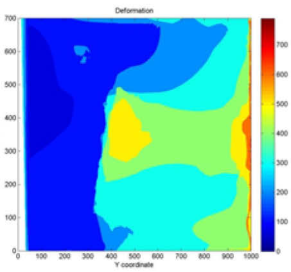
Row 3 + Row 4
2.6

DDY

Department of Automotive Engineering

- vehicle: 21_SFC_2_TRL
- vehicle width: 1783mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume	max def	U area		M area		L area		H (M area)		PPS
[l]	[mm]	score	def [mm]	score	def [mm]	score	def [mm]	score	TV	
133	446	1.1	336	1.6	439	2	303	1.2	1963	5.8

BDA software

M area + L area
164,611,553

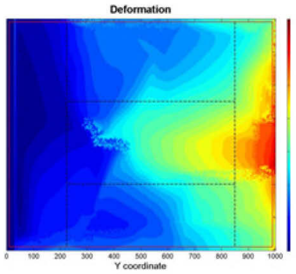
Homogeneity value

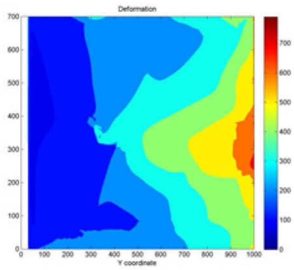
Row 3 + Row 4
1.7

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 18_SFC_3
- vehicle width: 1752mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
137	468	2	280	1.4	457	2	304	1.4	1742	6.7

BDA software

M area + L area
143,076,073

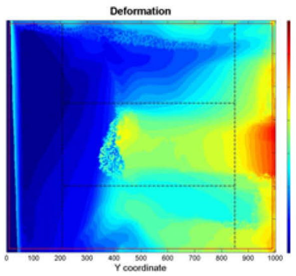
Homogeneity value

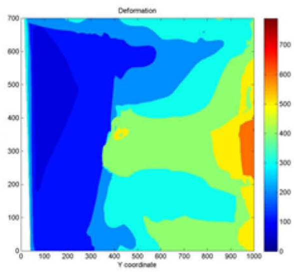
Row 3 + Row 4
1.1

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 07_SFC_2_serial
- vehicle width: 1783mm
- group: G2
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
141	424	2	276	1.8	414	2	353	0.9	2237	6.8

BDA software

M area + L area
148,335,514

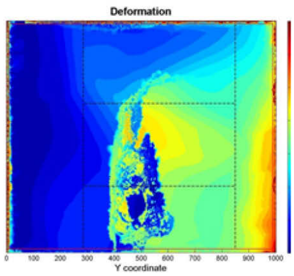
Homogeneity value

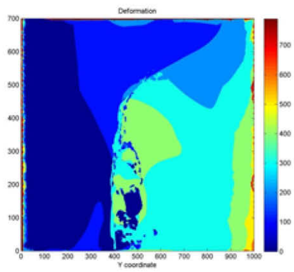
Row 3 + Row 4
1.7

DDY

Department of Automotive Engineering

- vehicle: FIMCAR_Supermini_2_RRSc_IDIADA
- vehicle width: 1627mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
156	479	0.4	376	3.5	465	1.9	428	0	3805	3.5

BDA software

M area + L area
38,180,200

Homogeneity value

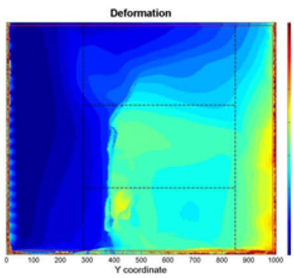
Row 3 + Row 4
0.6

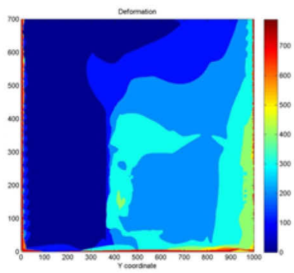
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 23

Department of Automotive Engineering

- vehicle: FIMCAR_Supermini_2_BASt_1
- vehicle width: 1627mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	TV	PPS
131	411	2	259	2	326	2	407	1.8	1245	7.8

BDA software

M area + L area
209,418,168

Homogeneity value

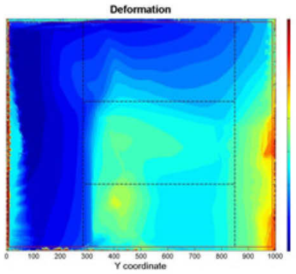
Row 3 + Row 4
0.6

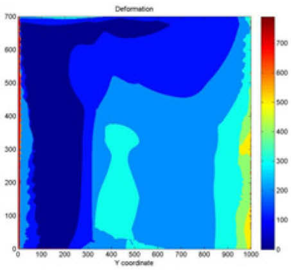
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 24

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: FIMCAR_Supermini_2_BASt_1
- vehicle width: 1627mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
143	392	2	234	2	324	2	383	1.9	1115	7.9

BDA software

M area + L area
284,247,959

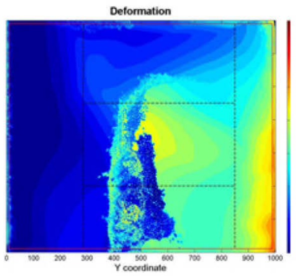
Homogeneity value

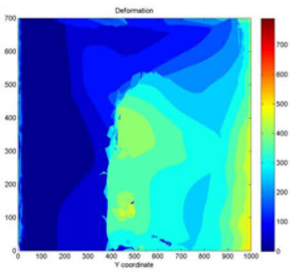
Row 3 + Row 4
1.0

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: FIMCAR_Supermini_2_FIAT
- vehicle width: 1627mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
125	482	1.1	335	1.8	422	2	401	0	3989	4.8

BDA software

M area + L area
122,006,265

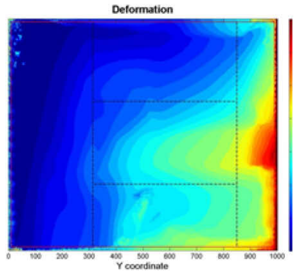
Homogeneity value

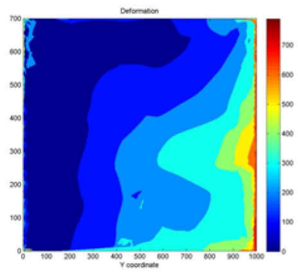
Row 3 + Row 4
0.6

DDY

Department of Automotive Engineering

- vehicle: 55_SFC_3
- vehicle width: 1572mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
129	413	2	196	2	398	2	347	1.9	1168	7.8

BDA software

M area + L area
190,144,805

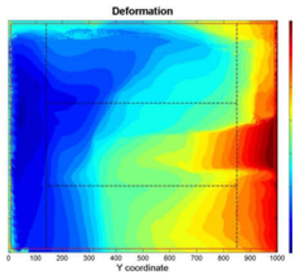
Homogeneity value

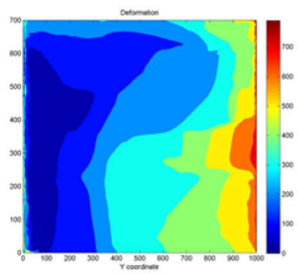
Row 3 + Row 4
0.7

DDY

Department of Automotive Engineering

- vehicle: 54_SUV_4_with_ACE
- vehicle width: 1920mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
200	559	1.3	322	0.5	534	1.7	457	1.7	1393	5.2

BDA software

M area + L area
240,470,555

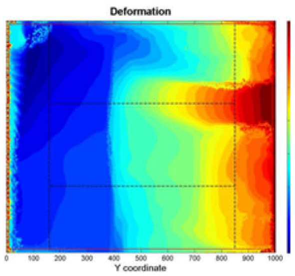
Homogeneity value

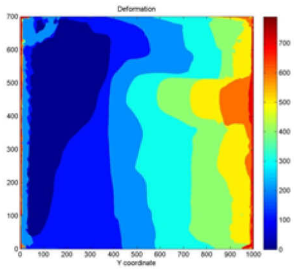
Row 3 + Row 4
1.7

DDY

Department of Automotive Engineering

- vehicle: 50_SUV_3
- vehicle width: 1880mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
196	596	0	493	0.2	560	1.9	411	1.9	1082	4.1

BDA software

M area + L area
232,011,092

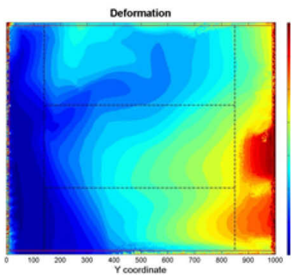
Homogeneity value

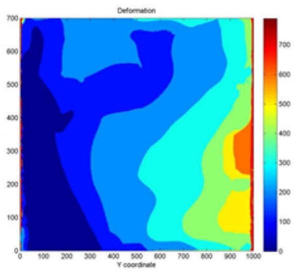
Row 3 + Row 4
1.2

DDY

Department of Automotive Engineering

- vehicle: 49_MPV_1
- vehicle width: 1920mm
- group: G1
- barrier depth: 790mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
175	502	1.9	285	1.7	425	1.9	422	1.9	1112	7.4

BDA software

M area + L area
291,113,869

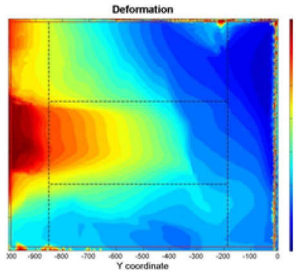
Homogeneity value

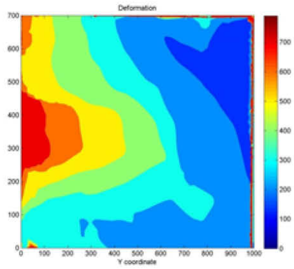
Row 3 + Row 4
0.7

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 47_Large_car_4
- vehicle width: 1830mm
- group: G1
- barrier depth: 700mm
- driver position: RHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
195	564	0.3	381	0.3	551	2	344	1.9	1145	4.5

BDA software

M area + L area
148,682,153

Homogeneity value

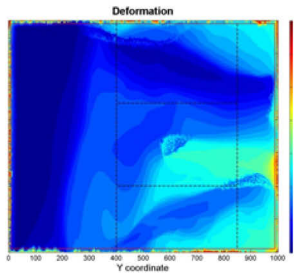
Row 3 + Row 4
0.8

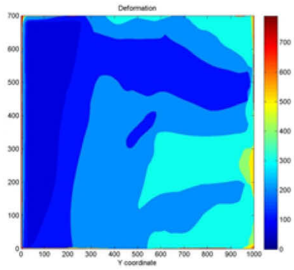
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 31

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 46_Supermini_3
- vehicle width: 1397mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
92	295	2	215	2	215	2	253	1.4	1732	7.4

BDA software

M area + L area
152,047,152

Homogeneity value

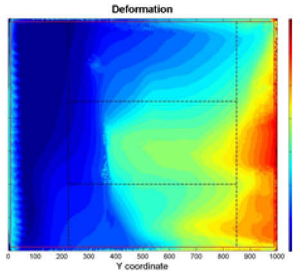
Row 3 + Row 4
0.7

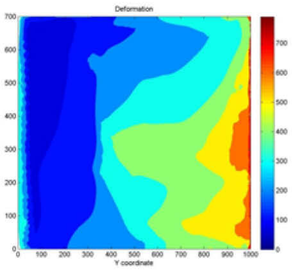
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 32

Department of Automotive Engineering

- vehicle: 34_SFC_homolo
- vehicle width: 1751mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
152	477	2	260	1.6	439	1.9	416	1.8	1295	7.2

BDA software

M area + L area
206,548,218

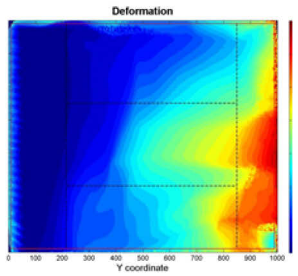
Homogeneity value

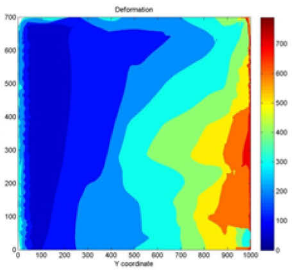
Row 3 + Row 4
1.0

DDY

Department of Automotive Engineering

- vehicle: 33_Medium_car
- vehicle width: 1770mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
138	549	2	268	1.5	448	2	381	1.6	1424	7.1

BDA software

M area + L area
139,433,536

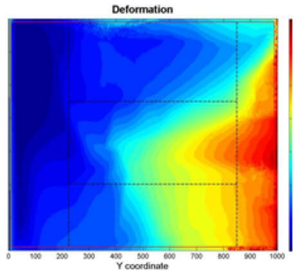
Homogeneity value

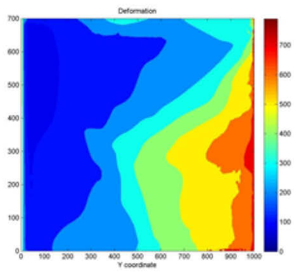
Row 3 + Row 4
1.0

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 29_SFC_3_homolo
- vehicle width: 1752mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
155	542	2	230	0.6	523	1.8	428	1.6	1461	6.1

BDA software

M area + L area
154,667,587

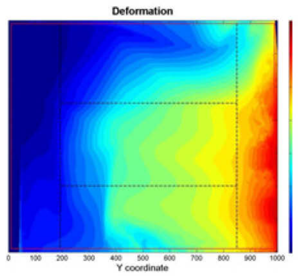
Homogeneity value

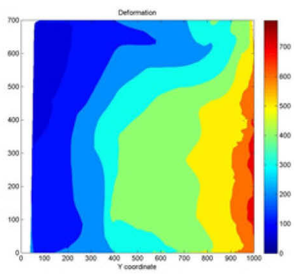
Row 3 + Row 4
1.2

DDY

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

- vehicle: 15_Large_car_3_DAG
- vehicle width: 1815mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
169	467	0.7	357	1.5	448	2	401	2	873	6.2

BDA software

M area + L area
299,503,392

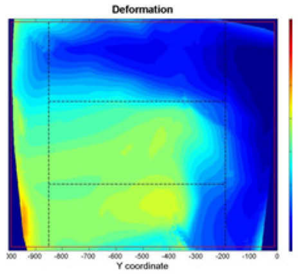
Homogeneity value

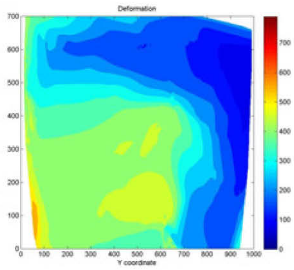
Row 3 + Row 4
0.6

DDY

Department of Automotive Engineering

- vehicle: 12_Large_car_3_DAD
- vehicle width: 1815mm
- group: G1
- barrier depth: 700mm
- driver position: RHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
143	399	2	255	2	365	2	396	2	1022	8

BDA software

M area + L area
302,384,904

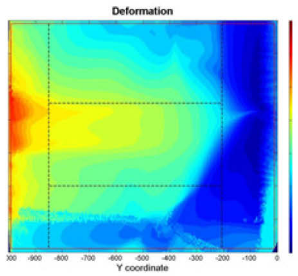
Homogeneity value

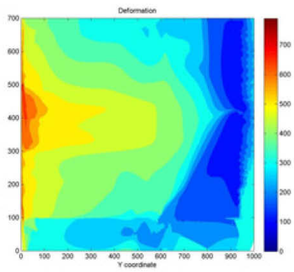
Row 3 + Row 4
0.3

DDY

Department of Automotive Engineering

- vehicle: 10_Large_car_2_DAD
- vehicle width: 1788mm
- group: G1
- barrier depth: 700mm
- driver position: RHD



volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
181	450	0.2	386	1.6	436	2	335	2	843	5.8

BDA software

M area + L area
259,185,762

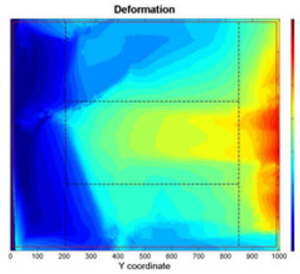
Homogeneity value

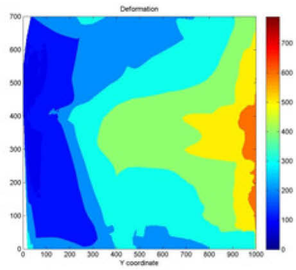
Row 3 + Row 4
0.4

DDY

Department of Automotive Engineering

- vehicle: 08_Large_car_2_DAG
- vehicle width: 1788mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
170	452	1.2	328	1.6	437	2	307	1.9	1097	6.7

BDA software

M area + L area
274,825,181

Homogeneity value

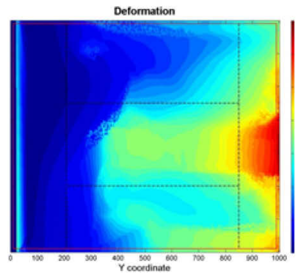
Row 3 + Row 4
0.7

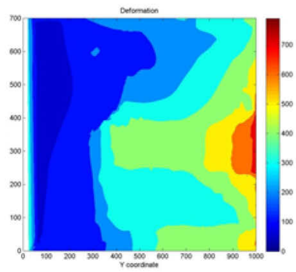
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 39

Department of Automotive Engineering

- vehicle: 06_SFC_2_stiff
- vehicle width: 1783mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
142	460	2	253	1.5	447	2	354	1.4	1750	6.8

BDA software

M area + L area
189,625,949

Homogeneity value

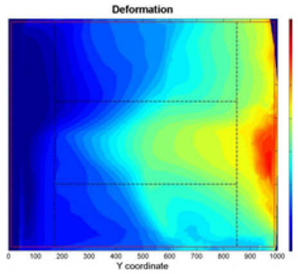
Row 3 + Row 4
1.2

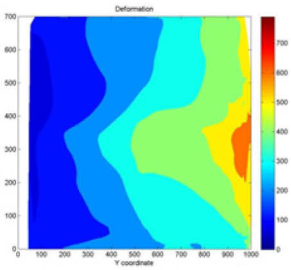
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 40

Department of Automotive Engineering

- vehicle: 04_Large_car_1
- vehicle width: 1853mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
145	426	1.8	292	1.8	414	2	304	1.8	1227	7.5

BDA software

M area + L area
214,125,085

Homogeneity value

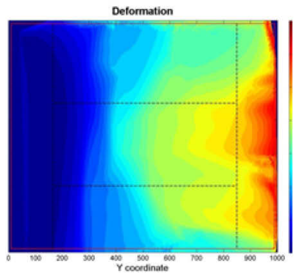
Row 3 + Row 4
1.5

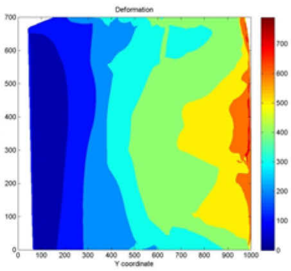
DDY

Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 41

Department of Automotive Engineering

- vehicle: 02_LCV
- vehicle width: 1870mm
- group: G1
- barrier depth: 700mm
- driver position: LHD





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
164	465	0.2	388	1.4	455	2	403	2	994	5.6

BDA software

M area + L area
243,894,954

Homogeneity value

Row 3 + Row 4
1.5

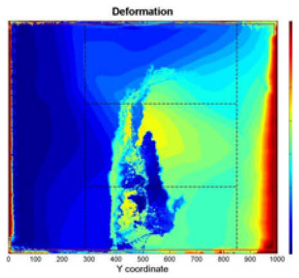
DDY

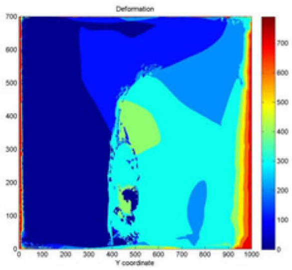
Mathias Stein FIMCAR – WP 2 – Vehicle PDB Profiles 42

FIMCAR frontal impact and compatibility assessment research

Department of Automotive Engineering

- vehicle: FIMCAR_Supermini_2_RR_Sc_TUB
- barrier depth: 790mm
- vehicle width: 1627mm
- driver position: LHD
- group: G1





volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
146	461	0.8	354	1.6	439	1.8	443	0	4016	4.1

BDA software

M area + L area
41,828,238

Homogeneity value

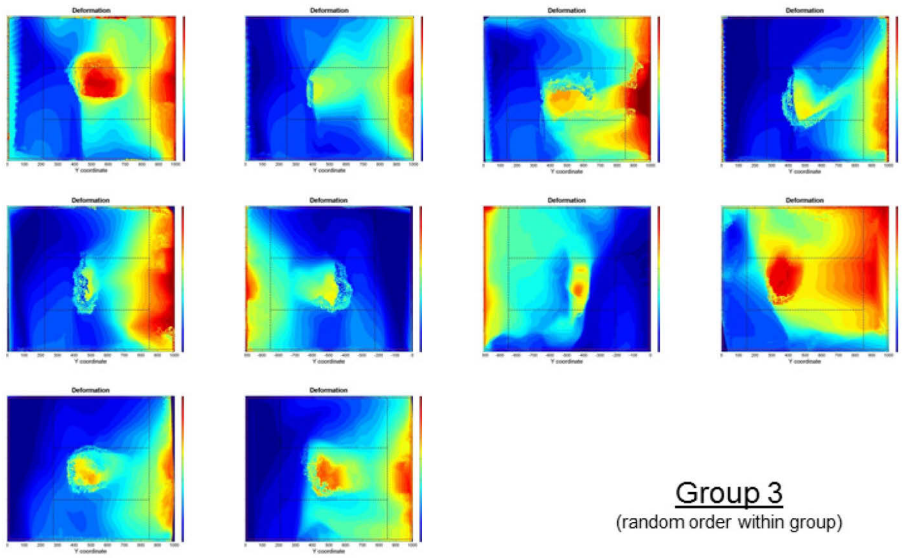
Row 3 + Row 4
0.6

DDY

FIMCAR frontal impact and compatibility assessment research

Department of Automotive Engineering

Subjective Classification w.r.t D2.1



Group 3

(random order within group)

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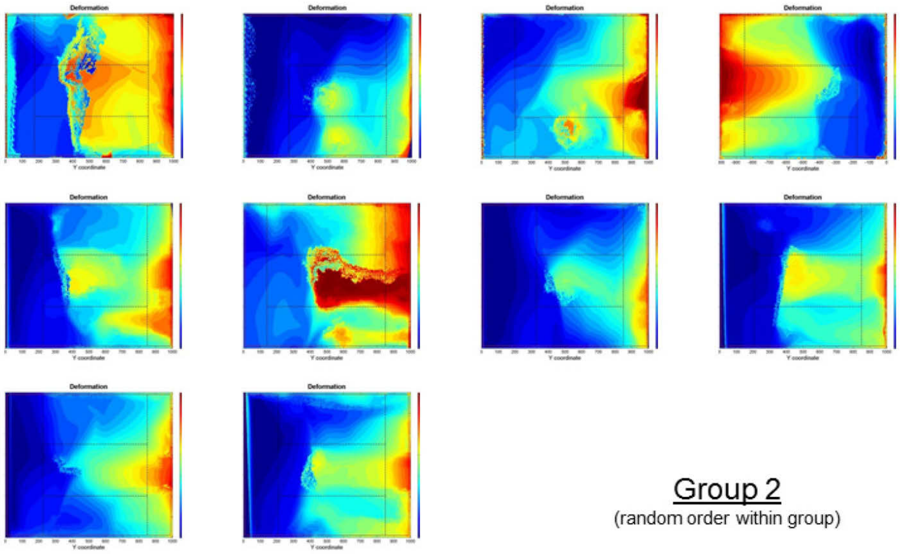
Subjective Classification w.r.t D2.1



Group 2
(random order within group)

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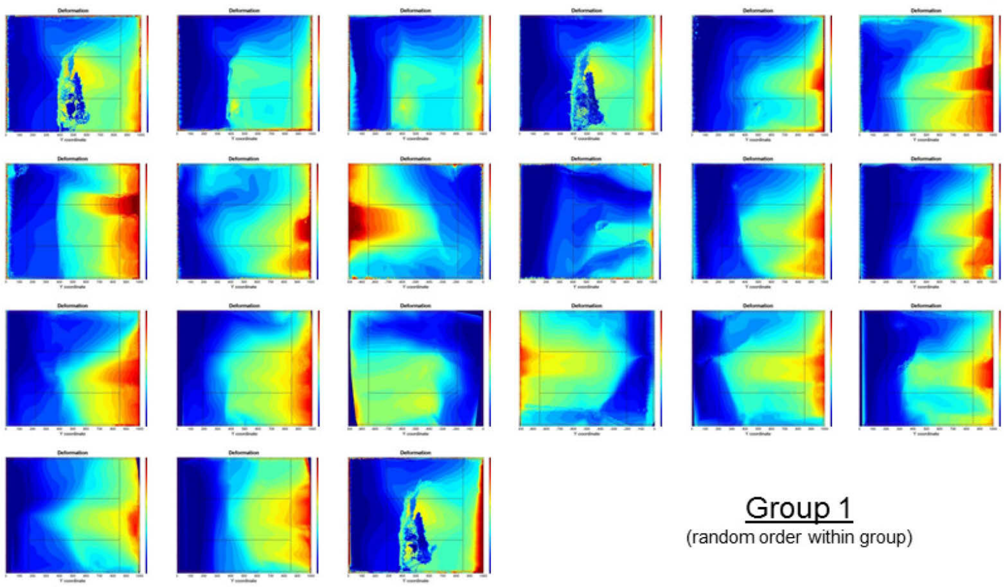
Subjective Classification w.r.t D2.1



Group 1
(random order within group)

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

PDB metric results

- **Summary of BDA assessment:**

group	vehicle	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
	FIMCAR_SFC_1	200	646	0	545	0	638	2	304	1.2	1966	3.2
	FIMCAR_Supermini_1_UTAC	146	415	1.3	321	2	402	2	246	1.3	1826	6.6
	56_SUV_4_without_ACE	185	579	1.3	320	0.8	504	1.8	431	0	3390	4
	52_Supermini_6	116	451	2	169	1.6	437	2	341	0	3819	5.6
G3	37_Small_SUV	157	570	1	339	1	489	1.8	430	0.1	3131	4
	19_Supermini_5_DAD	110	433	2	170	1.8	419	2	265	0	3626	5.8
	17_SUV_7	137	537	1.6	303	0.9	500	2	358	0.7	2444	5.2
	11_SUV_6	252	629	0	509	0	624	1.8	431	0	1459	1.8
	09_Supermini_5_DAG	117	502	2	184	1.2	474	2	300	0	3433	5.2
	05_SFC_2_weak	138	558	2	252	0.5	534	2	336	0.1	3160	4.6
	FIMCAR_SFC_1	228	582	0	548	0.1	568	1.5	495	0	3792	1.6
	FIMCAR_City_Car_1_UTAC	104	425	2	153	2	390	1.9	417	0.8	2373	6.7
	53_Family_car	189	589	1.6	302	0.7	518	1.4	513	1.7	1364	5.4
	48_SUV_5	212	591	0	477	0	577	2	367	0	1438	2
	35_SFC_3_repeat	154	488	1.1	333	1.7	431	1.8	435	1	2207	5.5
G2	30_SUV_4	231	694	0	511	0	692	1.4	496	0	3599	1.4
	28_Supermini_4	99	344	2	218	2	339	2	258	1	2135	7
	21_SFC_2_TRL	133	446	1.1	336	1.6	439	2	303	1.2	1963	5.8
	18_SFC_3	137	468	2	280	1.4	457	2	304	1.4	1742	6.7
	07_SFC_2_serial	141	424	2	276	1.8	414	2	353	0.9	2237	6.8

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

PDB metric results

- **Summary of BDA assessment:**

group	vehicle	volume [l]	max def [mm]	U area score	U area def [mm]	M area score	M area def [mm]	L area score	L area def [mm]	H (M area) score	H (M area) TV	PPS
	FIMCAR_Supermini_2_RRSc_IDIADA	156	479	0.4	376	3.5	465	1.9	428	0	3805	3.5
	FIMCAR_Supermini_2_BASt_1	131	411	2	259	2	326	2	407	1.8	1245	7.8
	FIMCAR_Supermini_2_BASt_1	116	451	2	169	1.6	437	2	341	0	3819	5.6
	FIMCAR_Supermini_2_FIAT	125	482	1.1	335	1.8	422	2	401	0	3989	4.8
	55_SFC_3	129	413	2	196	2	398	2	347	1.9	1168	7.8
	54_SUV_4_with_ACE	200	559	1.3	322	0.5	534	1.7	457	1.7	1393	5.2
	50_SUV_3	196	596	0	493	0.2	560	1.9	411	1.9	1082	4.1
	49_MPV_1	175	502	1.9	285	1.7	425	1.9	422	1.9	1112	7.4
	47_Large_car_4	195	564	0.3	381	0.3	551	2	344	1.9	1145	4.5
	46_Supermini_3	92	295	2	215	2	215	2	253	1.4	1732	7.4
G1	34_SFC_homolo	152	477	2	260	1.6	439	1.9	416	1.8	1295	7.2
	33_Medium_car	138	549	2	268	1.5	448	2	381	1.6	1424	7.1
	29_SFC_3_homolo	155	542	2	230	0.6	523	1.8	428	1.6	1461	6.1
	15_Large_car_3_DAG	169	467	0.7	357	1.5	448	2	401	2	873	6.2
	12_Large_car_3_DAD	143	399	2	255	2	365	2	396	2	1022	8
	10_Large_car_2_DAD	181	450	0.2	386	1.6	436	2	335	2	843	5.8
	08_Large_car_2_DAG	170	452	1.2	328	1.6	437	2	307	1.9	1097	6.7
	06_SFC_2_stiff	142	460	2	253	1.5	447	2	354	1.4	1750	6.8
	04_Large_car_1	145	426	1.8	292	1.8	414	2	304	1.8	1227	7.5
	02_LCV	164	465	0.2	388	1.4	455	2	403	2	994	5.6
	FIMCAR_Supermini_2_RR_Sc_TUB	146	461	0.8	354	1.6	439	1.8	443	0	4016	4.1

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

PDB metric results

- **Summary of Homogeneity value (TV upgraded) assessment:**

group	vehicle	M area + L area
G3	FIMCAR_SFC_1	47,915,147
G3	FIMCAR_Supermini_1_UTAC	100,495,224
G3	56_SUV_4_without_ACE	71,464,524
G3	52_Supermini_6	62,144,259
G3	37_Small_SUV	71,464,524
G3	19_Supermini_5_DAD	85,738,397
G3	17_SUV_7	74,689,634
G3	11_SUV_6	129,748,335
G3	09_Supermini_5_DAG	47,775,587
G3	05_SFC_2_weak	108,672,228
G2	FIMCAR_SUV_1_IDIADA	59,929,260
G2	FIMCAR_City_Car_1_UTAC	81,782,461
G2	53_Family_car	82,156,892
G2	48_SUV_5	189,619,514
G2	35_SFC_3_repeat	127,369,304
G2	30_SUV_4	57,173,388
G2	28_Supermini_4	131,503,576
G2	21_SFC_2_TRL	164,611,553
G2	18_SFC_3	143,076,073
G2	07_SFC_2_serial	148,335,514

group	vehicle	M area + L area
G1	FIMCAR_Supermini_2_RRSc_IDIADA	38,180,200
G1	FIMCAR_Supermini_2_BASt_1	209,418,168
G1	FIMCAR_Supermini_2_BASt_1	284,247,959
G1	FIMCAR_Supermini_2_FIAT	122,006,265
G1	55_SFC_3	190,144,805
G1	54_SUV_4_with_ACE	240,470,555
G1	50_SUV_3	232,011,092
G1	49_MPV_1	291,113,869
G1	47_Large_car_4	148,682,153
G1	46_Supermini_3	152,047,152
G1	34_SFC_homolo	206,548,218
G1	33_Medium_car	139,433,536
G1	29_SFC_3_homolo	154,667,587
G1	15_Large_car_3_DAG	299,503,392
G1	12_Large_car_3_DAD	302,384,904
G1	10_Large_car_2_DAD	259,185,762
G1	08_Large_car_2_DAG	274,825,181
G1	06_SFC_2_stiff	189,625,949
G1	04_Large_car_1	214,125,085
G1	02_LCV	243,894,954
G1	FIMCAR_Supermini_2_RR_Sc_TUB	41,828,238

Mathias Stein — FIMCAR – WP 2 – Vehicle PDB Profiles — 49

FIMCAR frontal impact and compatibility assessment research — Department of Automotive Engineering — TU berlin

PDB metric results

- **Summary of DDY assessment:**

group	vehicle	Row 3 + Row 4
G3	FIMCAR_SFC_1	7.1
G3	FIMCAR_Supermini_1_UTAC	1.4
G3	56_SUV_4_without_ACE	17.3
G3	52_Supermini_6	10.0
G3	37_Small_SUV	8.6
G3	19_Supermini_5_DAD	3.0
G3	17_SUV_7	6.6
G3	11_SUV_6	3.9
G3	09_Supermini_5_DAG	5.3
G3	05_SFC_2_weak	6.3
G2	FIMCAR_SUV_1_IDIADA	0.8
G2	FIMCAR_City_Car_1_UTAC	1.4
G2	53_Family_car	5.4
G2	48_SUV_5	1.5
G2	35_SFC_3_repeat	2.0
G2	30_SUV_4	15.7
G2	28_Supermini_4	2.6
G2	21_SFC_2_TRL	1.7
G2	18_SFC_3	1.1
G2	07_SFC_2_serial	1.7

group	vehicle	Row 3 + Row 4
G1	FIMCAR_Supermini_2_RRSc_IDIADA	0.6
G1	FIMCAR_Supermini_2_BASt_1	0.6
G1	FIMCAR_Supermini_2_BASt_1	1.0
G1	FIMCAR_Supermini_2_FIAT	0.6
G1	55_SFC_3	0.7
G1	54_SUV_4_with_ACE	1.7
G1	50_SUV_3	1.2
G1	49_MPV_1	0.7
G1	47_Large_car_4	0.8
G1	46_Supermini_3	0.7
G1	34_SFC_homolo	1.0
G1	33_Medium_car	1.0
G1	29_SFC_3_homolo	1.2
G1	15_Large_car_3_DAG	0.6
G1	12_Large_car_3_DAD	0.3
G1	10_Large_car_2_DAD	0.4
G1	08_Large_car_2_DAG	0.7
G1	06_SFC_2_stiff	1.2
G1	04_Large_car_1	1.5
G1	02_LCV	1.5
G1	FIMCAR_Supermini_2_RR_Sc_TUB	0.6

Mathias Stein — FIMCAR – WP 2 – Vehicle PDB Profiles — 50

Thorsten Adolph, Marcus Wisch, Mervyn Edwards, Robert Thomson,
Mathias Stein, Roberto Puppini

SEVENTH FRAMEWORK PROGRAMME

FIMCAR
VII –Full Width Test Procedure: Review and Metric Development

FIMCAR

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

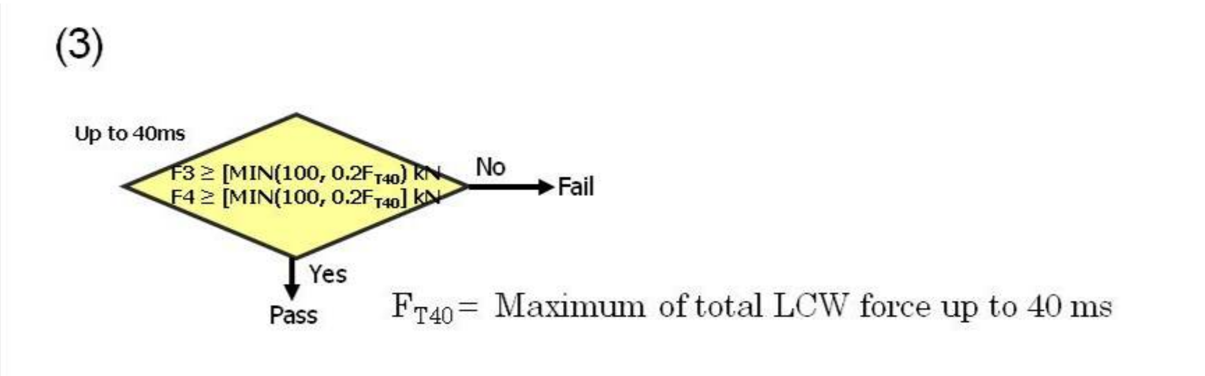
For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. Taking into account the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) and the FP5 VC-COMPAT project activities, two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

The overall objective of the FIMCAR project is to complete the development of the candidate test procedures and propose a set of test procedures suitable for regulatory application to assess and control a vehicle's frontal impact and compatibility crash safety. In addition an associated cost benefit analysis should be performed.

The objectives of the work reported in this deliverable were to review existing full-width test procedures and their discussed compatibility metrics, to report recent activities and findings with respect to full-width assessment procedures and to assess test procedures and metrics.

Starting with a review of previous work, candidate metrics and associated performance limits to assess a vehicle's structural interaction potential, in particular its structural alignment, have been developed for both the Full Width Deformable Barrier (FWDB) and Full Width Rigid Barrier (FWRB) tests. Initial work was performed to develop a concept to assess a vehicle's frontal force matching. However, based on the accident analyses performed within FIMCAR frontal force matching was not evaluated as a first priority and thus in line with FIMCAR strategy the focus was put on the development of metrics for the assessment of structural interaction which was evaluated as a first priority.

The FWDB and FWRB tests both have advantages and disadvantages. The metrics developed for these tests also have advantages and disadvantages. FIMCAR WP3 members have discussed these advantages and disadvantages and recommend that priority is given to the further development of the FWDB test and FWDB metric (3) as shown below.



The reasons for selecting the FWDB as 1st priority are:

- The FWDB test has the edge technically over the FWRB test because there is no need for a supplementary test. Also the structural interaction assessment is made later in the impact than for the FWRB test which, because the vehicle's crash structures are more fully loaded, allows a more meaningful assessment of them.

- The FWDB metric (3) is recommended because its correlation with a geometric assessment of the vehicle is as good as the other FWDB metric candidates, it is a single stage metric which follows the spirit of keeping the metric as simple as possible and effectively it allows the mass of the vehicle to be taken into account in the performance requirements.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. From the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) [Faerber 2007] and the FP5 VC-COMPAT project activities [Edwards 2007], two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

Within the FIMCAR project off-set, full overlap and MDB test and assessment procedures will be developed further with the ultimate aim to propose a compatibility assessment approach. This should be accepted by a majority of the involved industry and research organisations. The development work will be accompanied by harmonisation activities to include research results from outside the FIMCAR consortium and to disseminate the project results early, taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objectives of this Deliverable

The objectives of the work reported in this deliverable were to review existing full-width test procedures and their discussed compatibility metrics, to report recent activities and findings with respect to full-width assessment procedures, to assess test procedures and metrics and to start the development of FIMCAR metrics.

2 BACKGROUND

The overall aim of FIMCAR is to develop a suite of test procedures which address self and partner protection in order to decrease the injury risks in single and multiple vehicle frontal impact accidents. It is expected that compatible vehicles will deform in a stable manner allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved. In Europe, at present, one Offset Deformable Barrier (ODB) test procedure is used for regulatory and consumer testing. Essentially, this test procedure addresses a vehicle’s self protection but not its partner protection.

From a review of previous research, such as the EEVC WG15 [Faerber 2007], VC-COMPAT project [Edwards 2007], and IHRA [O'Reilly 2003], and additional accident analysis [Thompson 2013], FIMCAR members have set priorities for the development of the test procedures. The top priorities with respect to this report are that the test procedures should address structural interaction, high overlap collision types and the risk of injuries arising from acceleration loading.

The main structural interaction problems identified in FIMCAR Deliverable D1.1 [Thompson 2013] were under/overriding, low overlap and the fork effect. In order to address the under/overriding aspect of structural interaction, structural alignment was considered a necessary but not totally sufficient first step. To address structural alignment, it was decided to use the approach that all vehicles should have crash structures in alignment with a common interaction zone. The US voluntary commitment for a common vertical interaction zone [Barbat 2005] was considered as a good starting point. A further step to address under/overriding is load spreading in the vertical direction. This can be achieved with vehicles that have multi-level load paths and strong connections between them. Load spreading in the horizontal direction is also an important factor for prevention of the fork effect and addressing accidents with small overlaps. Strong cross beams can help provide good interaction in accidents with narrow objects and cross beams extending outboard from longitudinal members can improve structural interactions in cases with small overlap at the corners.

As regards the assessment of structural interaction, the approach proposed in FIMCAR is that structural alignment in the vertical direction is assessed with a full width test using a load Cell Wall (LCW). At the same time a small step towards the assessment of vertical load spreading can be achieved. It is proposed that this will be achieved using the ‘common interaction zone’ concept.

The purpose of the work reported in this document was to investigate further the use of a Full Width Rigid Barrier (FWRB) or Full Width Deformable Barrier (FWDB) test as a candidate for assessing structural alignment for vehicles. The test severity of the selected full width test should also promote further development of occupant restraint systems for additional protection in crashes with high acceleration levels such as high overlap cases. The possibility of introducing force matching metrics in a full width test has been investigated as it is desirable that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy. However this last item has not been judged as a first priority, because compartment strength of lighter cars was not identified as a specific issue in accident data analyses.

For both full width tests, Load Cell Wall (LCW) data is being investigated as a method to assess the structural interaction characteristics of a vehicle by measuring the vehicle’s force distribution. The current defacto standard for a LCW is one that consists **of 125 mm square elements** with the bottom row mounted with an **80 mm ground clearance** (Figure 2.1).

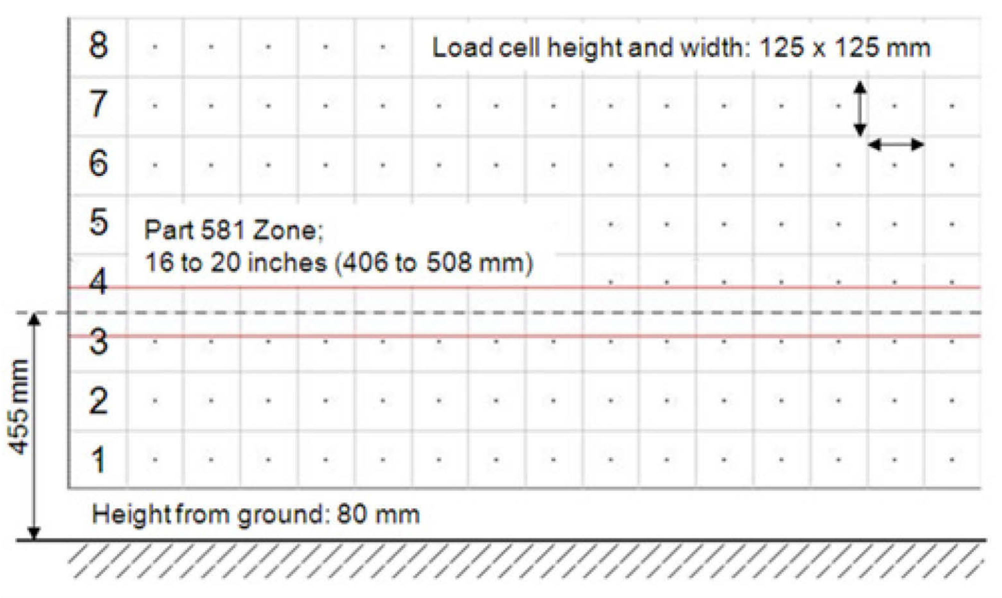


Figure 2.1: Overview of the specifications of the LCW (rows, columns, height of ground, Part 581 zone).

The FWRB test is conducted in many countries (USA, Canada, Japan etc.) for both regulation and consumer testing programs. Test speeds range from 50 km/h to 56 km/h. Instrumented Hybrid III dummies are typically used to measure occupant response.

The FWDB test has a 300 mm deep deformable element as shown in Figure 2.2 [Edwards 2003].

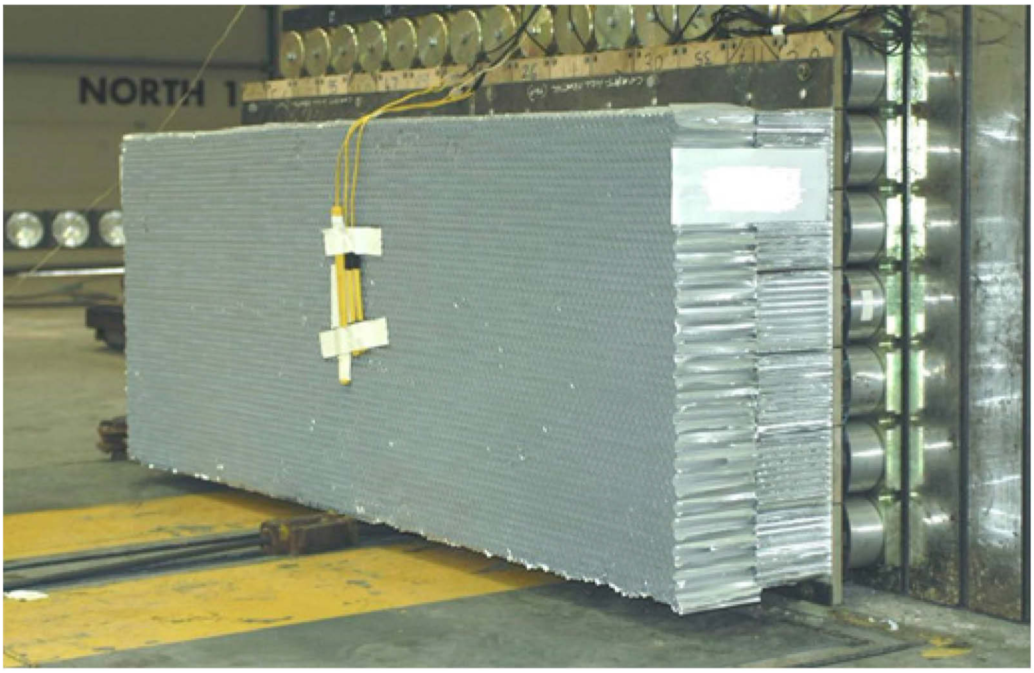


Figure 2.2: Full Width Deformable Barrier.

The FWDB is currently only used in research applications and is not part of a regulation or consumer test procedure. As with the FWRB, tests are conducted with Hybrid III dummies to assess occupant response. Although essentially the same test configuration as the FWRB, the additional honeycomb is included to help make the test more representative of real world accidents, especially in the initial stage of the impact. This is important for sensing of the crash for restraint system triggering. The barrier consists of two layers, each 150 mm deep. The first layer consists of 0.34 MPa axial crush strength honeycomb and the second layer 1.71 MPa crush strength honeycomb. The second layer is segmented into 125 mm x 125 mm blocks which align with the individual cells of the LCW to prevent the deformable face spreading loads applied in one area over a wider area on the LCW. The general hypothesis is that vehicles with better structural interaction potential should produce a more even load distribution in the FWDB test. The main purpose of the front layer is to attenuate engine dump loads and make them more similar to those seen in a car-to-car impact. The main purpose of the rear layer is to prevent localised stiff structures on the car, such as protruding bolts and towing eyes which would have little / no influence in a car-to-car impact, forming preferential load paths to the wall and hence altering the LCW force distribution in an unrepresentative manner by reducing the loading from adjacent structures [Edwards 2003]. Furthermore, the deformable face can help detect Secondary Energy Absorbing Structures (SEAS) and hence assess them because the deformable face 'reaches' into the vehicle and allows these structures to load the wall even though they may not be in direct contact with it. On the other hand, the possible risk of load spreading due to the deformable element can be counted as a disadvantage compared to the rigid barrier.

3 ASSESSMENT CRITERIA DEVELOPMENT

This section is divided into three parts. The first part describes a review of current and previous criteria. This determines a starting point for the development of a new / revised metric and helps to give an understanding of how to develop a metric. The second part describes the advantages and disadvantages of the Full Width Deformable Barrier (FWDB) and Full Width Rigid Barrier (FWRB) tests and the third part the development of the metrics. New metrics were developed for both the FWDB and FWRB tests including the development of proposals for performance limits.

3.1 Review of Current and Previous Assessment Criteria

Over the last ten years a number of assessment criteria have been developed for the Full Width Rigid Barrier (FWRB) and Full Width Deformable Barrier (FWDB) tests. The aim of these criteria was to assess and control a vehicle's compatibility, in particular its structural interaction potential and in some cases its stiffness. To date none of these criteria have been deemed suitable for consumer and / or regulatory testing. The sections below describe the main criteria developed for the FWDB and FWRB tests and the issues with them.

3.1.1 Full Width Deformable Barrier (FWDB)

Three main metrics have been developed for the FWDB test:

- Homogeneity Criterion
- Structural Interaction (SI) Criterion
- Force in a common interaction zone type metric

The development of the deformable face is reported by Edwards *et al.* [Edwards 2003]. The aim of the first two metrics, the homogeneity and structural interaction criteria, was to assess a vehicle's structural interaction potential. These metrics were based on an assessment of the force distribution on a high resolution LCW placed behind the barrier face following the hypothesis that vehicles with better structural interaction potential should give a more even load distribution on the LCW. It should be noted that the structural interaction criterion was developed to resolve issues with the homogeneity criterion. The aim of the third metric, force in a common interaction zone, was to assess a vehicle's structural alignment. This metric was based on the concept that vehicles with a strong structure in alignment with the common interaction zone should apply a high proportion of their load to the rows on the LCW in alignment with the zone.

These metrics and the issues associated with them are described in greater detail in the sections below.

3.1.1.1 Homogeneity Criterion

As mentioned above, the concept which this metric was based on was that vehicles with a better structural interaction potential should give a more even load distribution on the LCW. The homogeneity criterion assessed the LCW force distribution over a footprint [Figure 3.1]. The size of the footprint was defined individually for each vehicle and depended on the size and geometry of the vehicle.

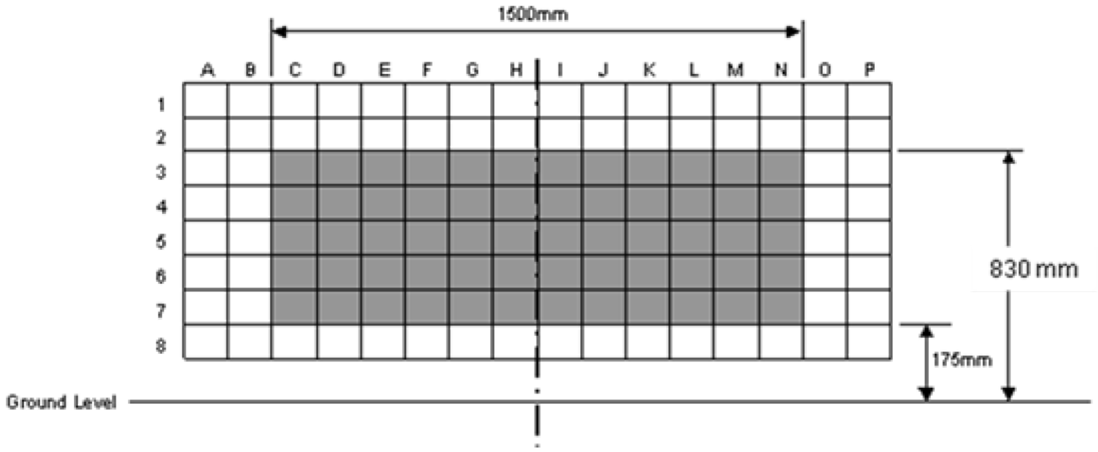


Figure 3.1: Typical dimensions of footprint for calculation of homogeneity criterion for mid-size car. Note in this case the LCW ground clearance was 50 mm. For later work this was increased to 80 mm.

Initially the LCW data was smoothed to reduce sensitivity of the metric to the alignment of the vehicle with the LCW. Following this, the metric was calculated by summing the difference squared between peak load (f) and an average load (L) for individual cells (H_{cl}), rows and columns within the vehicle footprint. The cells, rows and columns contributions were then weighted (if deemed necessary) and added together.

$$H_{cl} = \frac{\sum_{i=1}^{{}_s n} (L - {}_s f_i)^2}{{}_s n}$$

where ${}_s$n is the total number of cells within the vehicle footprint after smoothing

Further details of how to calculate this metric can be found in [Edwards 2003].

Later, this metric was developed further to take into account the mass of the vehicle being tested. Specifically, it was normalised using the average load as shown in the formula below and renamed the 'relative homogeneity criterion'.

$$RH_{cl} = \frac{H_{cl}}{L^2}$$

The following issues were found with the homogeneity criterion:

- Repeatability
  - The sensitivity of the metric to impact alignment was found to be too high to allow acceptable test to test repeatability. This was despite the fact that the LCW data were smoothed to attempt to reduce this.
- Effect of data smoothing
  - Effectively, this caused a reduction in the resolution of the metric and an inability to distinguish adequately between some vehicles.
- Definition of assessment area

  - An objective methodology to determine the footprint (assessment area) for each individual vehicle could not be derived.
- Bottoming out of the barrier face
  - In tests some vehicles bottomed out the barrier face and directly contacted the LCW whereas others did not. There appeared to be a discontinuity in the homogeneity assessment values for these two sets of vehicles which was not dependent on the vehicle's structural interaction potential.

To try and resolve these issues the structural interaction criterion was developed.

3.1.1.2 Structural Interaction (SI) Criterion

The Structural Interaction (SI) criterion was developed to resolve issues with the Homogeneity Criterion. Its development was based on the following requirements:

- An ability to be applied in a stepwise manner to allow manufacturers to gradually adapt vehicle designs
- To encourage better horizontal force distribution (crossbeams).
- To encourage better vertical force distribution (multi-level load paths).
- To encourage a common interaction area with minimum load requirement.

Compared to using peak cell loads recorded throughout the duration of the impact (as with the previous homogeneity criterion), the SI criterion was calculated from the peak cell loads recorded in the first 40 ms of the impact. This has the advantage of assessing structural interaction at the beginning of the impact when it can be more effective and minimising the loading applied by structures further back into the vehicle such as the engine. The 40 ms time interval corresponds to a B-pillar displacement (including barrier crush) of approximately 550 mm for most cars [Figure 3.2].

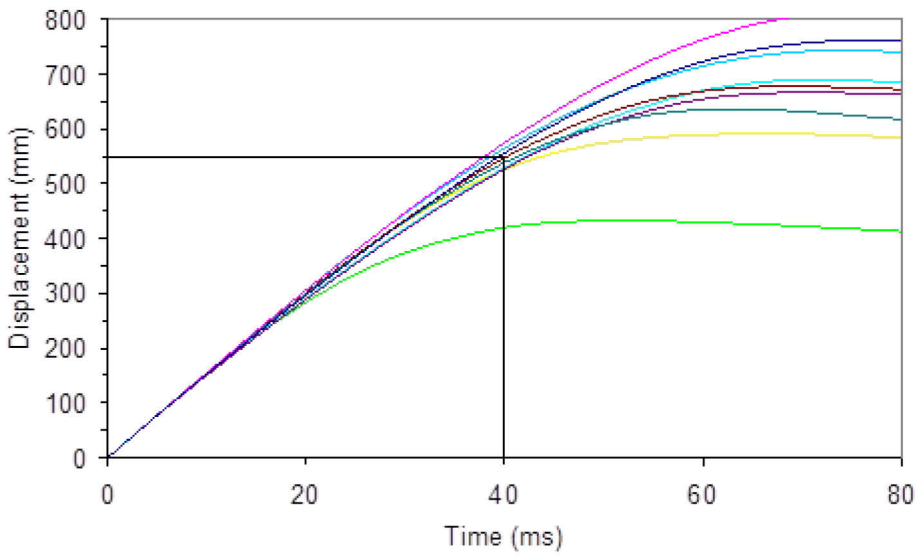


Figure 3.2: B-pillar displacement vs. time plots for FWDB tests. The outlier is a supermini car with unique short stiff frontal structure which restricts its deformation.

Based on the assumption that structures which only crush the 150 mm softer front layer of the barrier will not apply sufficient load to the LCW to be adequately detected, this criteria should allow the detection of structures up to 400 mm (550 mm -150 mm) from the front of the vehicle. This is adequate for detection of most Secondary Energy Absorbing Structures (SEAS), such as subframes, that interact with the partner vehicle in a crash.

To allow manufacturers to gradually adapt vehicle designs to become more compatible, the SI criterion consisted of two parts which could be adopted in a stepwise manner. The first part assessed the forces on the LCW over a common interaction area, an area from 330 mm to 580 mm above ground level, LCW Rows 3 and 4 (Area 1), (Figure 3.3). The intention of this part of the assessment was to ensure that all vehicles had adequate structure in alignment with the common interaction area to ensure good interaction. The second part assessed the forces over a larger area, from 205 mm to 705 mm above ground level, LCW Rows 2, 3, 4 and 5, (Area 2). The intention of this part of the assessment was to encourage cars to distribute their load more homogeneously over a larger area to reduce the likelihood of over/under-ride and the fork effect.

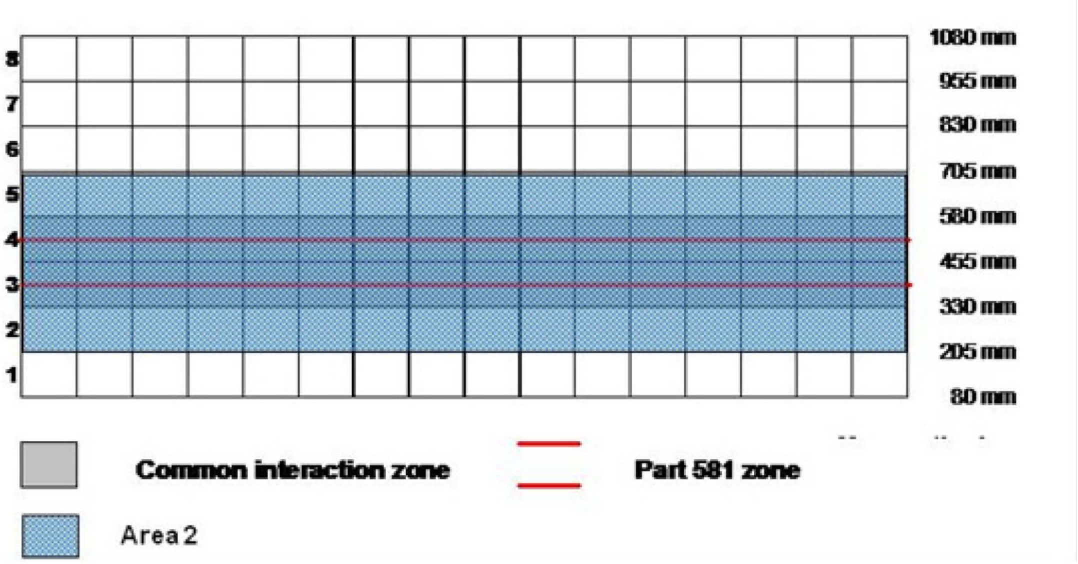


Figure 3.3: Assessment areas for Structural Interaction metric.

Each part of the SI assessment consisted of two components, a vertical component (VSI) and a horizontal component (HSI). The aims of the various parts of the metric are summarised below:

- Vertical component (VSI)
  - Area 1 – common interaction area (Rows 3 & 4)
  - To encourage structural alignment using a requirement of a minimum load of 100 kN in Rows 3 & 4
  - Area 2 (Rows 2, 3, 4 & 5)
  - To encourage vehicles to distribute their loads better vertically using a combination of minimum load and even distribution of load requirements.
- Horizontal component (HSI)
  - Area 1 and 2
  - To encourage vehicles to have strong crossbeam connections which are matched to the strength of the rail.

Further details of how to calculate this metric can be found in [Edwards 2007].

The following issues were found with the structural interaction criterion:

- Repeatability
  - Poor repeatability was observed with the horizontal component of the metric in tests performed in the APROSYS EC 6th framework project [Edwards 2008].
- Differentiation
  - For the SI criterion for Area 2, generally SUVs gave much higher values than cars. Hence, it was not possible to set performance limits that were appropriate to encourage both cars and SUVs to improve their structural interaction potential.
- Complexity
  - In general, the SI criterion was quite complex and difficult to understand.

3.1.1.3 Force in a common interaction zone metric

This metric was developed to enhance the US voluntary commitment for the improvement of the geometric frontal impact compatibility of Light Trucks and Vans (LTVs) [Barbat 2005] and resolve the issues with the Structural Interaction metric described above.

The aim of the US voluntary commitment is to ensure that LTVs have structure in alignment with a common interaction zone from 16 to 20 inches (406 – 508 mm), further named as “Part 581 zone”) measured vertically from the ground (Figure 3.4) to enable better interaction with cars. The US voluntary commitment states that all LTVs sold by participating manufacturers in the US should fulfil one of the options below:

OPTION 1

The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone (Option 1a)

AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2

If a light truck does not meet the criteria of Option 1, there must be a secondary energy absorbing structure (SEAS), connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone.

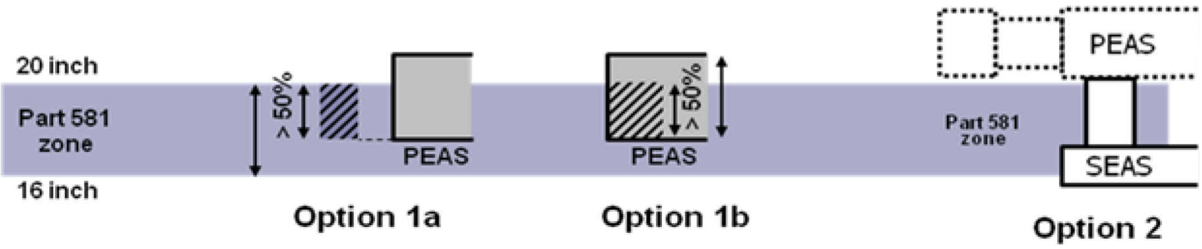


Figure 3.5. US voluntary commitment for improved compatibility of LTVs.

It should be noted that the US voluntary commitment was not felt to be appropriate for regulatory application because ideally regulations should be ‘performance based’ and the voluntary commitment is ‘design based’. A design based requirement is generally more restrictive for the layout of a vehicle than a performance based one and hence is less desirable for regulatory application. However, sometimes design based regulations are the only option.

Using accident data analysis, the IIHS have shown that the introduction of the US voluntary commitment has helped to reduce casualties in LTV to car crashes [Teoh 2011].

The US Enhanced Vehicle Compatibility (EVC) Working Group investigated the potential of the FWDB test to assess and control Light Truck or Van (LTV) compatibility [Barbat 2005] based on the concept of controlling the force measured on the LCW in alignment with a common interaction zone. They found that metrics to control the load applied to Rows 3 and 4 such as:

‘Sum of peak cell loads up to end of impact ≥ 100 kN

‘Sum of peak cell loads before 40 ms ≥ 100 kN

could distinguish between:

- An LTV with its main Primary Energy Absorbing Structures (PEAS) in alignment with the Part 581 zone and the same LTV raised 100 mm so that its PEAS were not in alignment with the Part 581 zone.
- An LTV with and without Secondary Energy Absorbing Structures (SEAS)

		Sum of peak cell loads (kN)		Sum of peak cell loads up to 40ms (kN)	
		Row 3	Row 4	Row 3	Row 4
LTV1	Standard	279	328	205	321
	Raised	94	447	45	397
LTV2	Standard	136	242	109	212
	No SEAS	91	129	56	68

Figure 3.6: Metric values for LTV tests showing that the metric can distinguish between vehicles with and without structure in alignment with Part 581 zone. Note: the ‘Sum of peak cell loads before 40 ms’ metric is identical to the vertical component of Structural Interaction criterion for the ‘Area 1’ assessment [Verma 2007].

It should be noted that this work was focused on LTVs and later research with cars found that some lighter cars could not meet the performance limit of 100 kN proposed for LTVs even if they had their main structure in alignment with the common interaction zone.

3.1.2 Full Width Rigid Barrier (FWRB)

Three main metrics have been previously developed for the FWRB test:

- Average height of Force 400 (AHOF400)
- Stiffness matching or frontal force control (KW 400)
- Force in a common interaction zone type metric

The first two metrics were developed by the US National Highway and Traffic Safety Administration (NHTSA) and the third by Nagoya University on behalf of the Japanese government. The metrics are described further in the sections below.

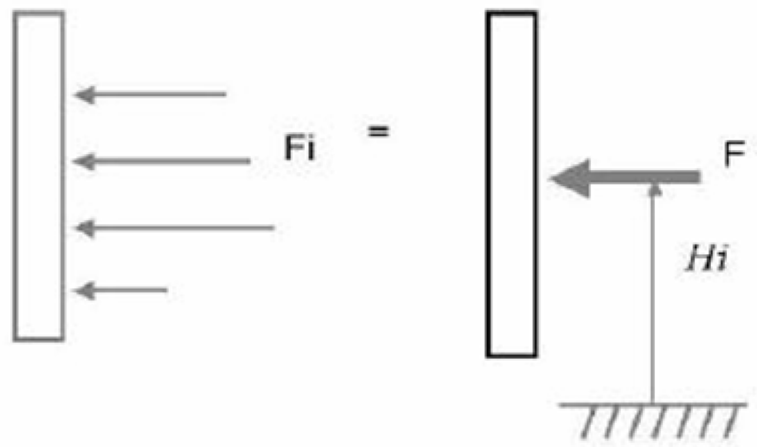
One major issue with the rigid barrier test regarding the assessment of a vehicles structural interaction potential is that, in general, it is only suitable for the assessment of vehicle’s which have their Primary Energy Absorbing Structure in alignment with the common interaction zone and it is not suitable for vehicle’s which have Secondary Energy Absorbing Structure (SEAS) in alignment with the common interaction zone. This is because the rigid barrier test is not particularly representative of a vehicle-to-vehicle impact as regards loading of SEAS, especially for SEAS that are attached directly to the PEAS. This is because, in general, the front of a vehicle's SEAS is positioned behind the front of a vehicle's PEAS. Hence in a rigid barrier test the PEAS are always loaded fully when the SEAS are loaded, whereas in a vehicle-to-vehicle impact the PEAS may not be loaded fully when the SEAS are loaded. For example, a vehicle's PEAS may over-ride the structure of its impact partner. In the case where a vehicle's SEAS are directly connected to its PEAS, deformation of the PEAS behind the position where the SEAS are connected can occur in a rigid barrier test. This can cause the SEAS to move rearwards without actually been loaded directly by the wall. This results in LCW forces which are not representative of the loading that the SEAS would experience in a vehicle-to-vehicle impact and hence an incorrect assessment of the vehicle.

To resolve this issue NHTSA proposed a supplementary Over-Ride Barrier (ORB) test to assess the structural interaction potential of vehicles which have their SEAS in alignment with the common interaction zone. Generally these vehicles are 'high' vehicles such as Light Trucks and Vans (LTVs) or vehicles such as SUVs designed to have off-road capability. The ORB test and its associated metrics are described further below.

3.1.2.1 AHOF400

The Average Height of Force 400 (AHOF400) is the average height of force that the vehicle applies to the LCW during its first 400 mm of crush [Patel 2007]. The aim of the AHOF400 metric is to control the vertical positioning of a vehicle's structures to ensure that the vehicle has structure in alignment with the common interaction zone. Precise performance limits have not been proposed for this metric although they would likely be in the region of the Part 581 zone. It is calculated as shown in Figure 3.7. First, the Height of Force (HOF) is estimated by multiplying the individual cell force by the height of the middle of that cell above ground, summing this for all cells and dividing this summation by the total wall force. Next the AHOF400 is calculated by averaging the weighted HOF for the period in which the vehicle crushes from 25 mm to 400 mm. This crush range was used to eliminate the noise in the data in the first 25 mm of crush when the relatively soft bumper engages the wall and is limited to a maximum crush of 400 mm to include the forces exerted on the wall by the rails buckling, but stop before the engine contact exerts significant forces. The vehicle crush is calculated from a double integration of an accelerometer trace mounted in the vehicle's compartment.

Issues regarding AHOF400 include that it is only suitable for the assessment of vehicles which have their PEAS in alignment with the common interaction zone. As mentioned above, a supplementary test (e.g. the ORB test) is also needed to assess vehicles which have their SEAS in alignment with the common interaction zone. Other issues include that further work is needed to prove that AHOF400 metric is appropriate and to derive performance limits.



$$HOF(d) = \frac{\sum_{i=1}^{i=n} Fi(d) * Hi}{\sum_{i=1}^{i=n} Fi(d)} \qquad AHOF400 = \frac{\sum_{d=25mm}^{d=400mm} HOF(d) * F(d)}{\sum_{d=25mm}^{d=400mm} F(d)}$$

Figure 3.7: Calculation of AHOF400.

3.1.2.2 Stiffness Matching and KW 400

One objective for compatibility that has been investigated previously has been to control the frontal interactions between vehicles to avoid overcrushing of energy absorbing structures of smaller vehicles. As shown in Figure 3.8, the compartment strength of vehicles is generally related to the mass of the vehicle. The frontal force levels are lower than the compartment forces for a given vehicle to ensure that the compartment is intact while the front deforms and absorbs energy. The problem with frontal force mismatch between vehicles is highlighted in Figure 3.8 where the heavier vehicle's force levels exceed the compartment strength of the small car. This force mismatch is caused by some extent to the current regulations and the tendency for manufacturers to minimise the vehicle's deformation zone for more effective packaging. The current regulations effectively enforce that in a crash test a vehicle has to be able to absorb its kinetic energy in its frontal crash structure. Hence, a heavier vehicle's frontal structure has to be able to absorb more energy than a lighter vehicle's because it has more kinetic energy. Therefore, if a heavy vehicle's deformation zone is a similar length to that of a lighter vehicle the heavier vehicle will have to have higher force levels in its frontal structure than a lighter vehicle to absorb the additional kinetic energy. Hence the force/mass relationship shown in the figure is common for modern vehicles [Faerber 2007, Edwards 2007].

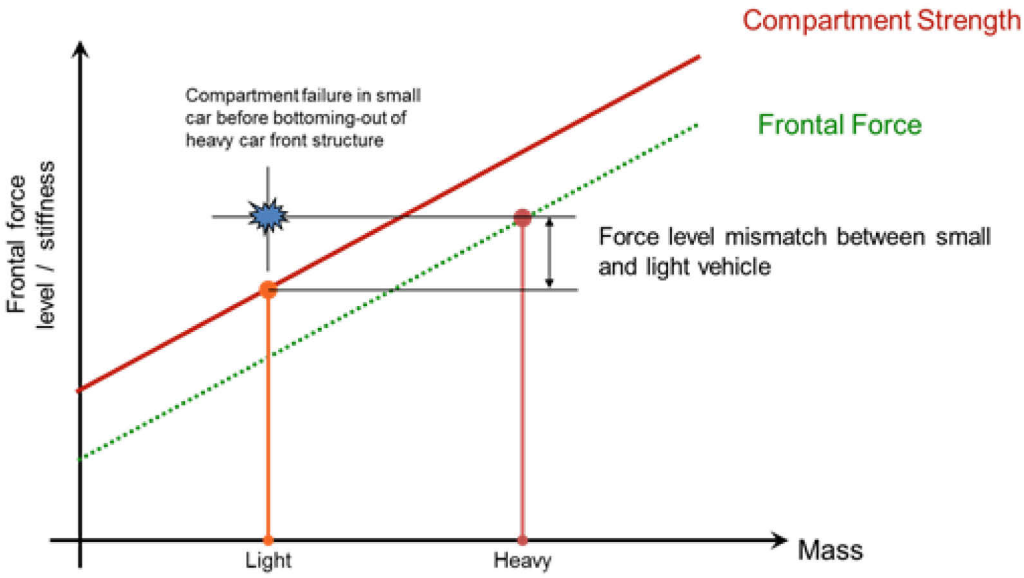


Figure 3.8: Basic concepts for front unit and compartment strengths.

There is a desire to promote better structural interaction between vehicles but there are still concerns that the stiffness levels between vehicles should not be allowed to develop unrestricted so that a very stiff vehicle can cause deformations of a partner vehicle's compartment due to incompatible force levels. There are constraints on this issue as it is not feasible to extend this requirement over the full range of vehicle sizes (0.8 to 3.5 t) due to likelihood of collisions and side effects for vehicle design (extended lengths and increased mass). Previous work recommends force matching over a mass ratio of 1:1.6 [Faerber 2007, Edwards 2007] for smaller vehicles (around 1 t) based on accident analyses.

Although the concept of force/stiffness matching may be encountered in literature, few concrete examples of evaluation metrics have been derived. Van der Zweep [van der Zweep 2006] evaluated the minimum force levels for smaller cars in the VC-Compat project. The use of 350-400 kN as a minimum compartment strength showed promise as a reference occupant survival in 1,200 kg vehicles colliding with vehicles 1.6-1.7 times heavier. This value has not been connected to a force requirement other than the proposal by TRL in VC-Compat to use the ODB test to ensure a minimum vehicle strength. VC-Compat did not develop any further force matching criteria.

The most discussed force matching criterion was developed at NHTSA and is called the KW 400 [Patel 2007]. The metric, expressed in the following equation, measures the work dissipated in the deformation of the vehicle between 25 and 400 mm of crush in a full width frontal impact with a rigid barrier and estimates the initial slope of the force/deflection curve for the vehicle in a car-barrier impact. Figure 3.9 shows the energy and slope calculated in KW 400.

There have been different issues raised in conjunction with the KW 400. An initial issue is the calculation of the displacement information as this currently is found by the double integration from a vehicle accelerometer signal and must be synchronized with the load cell data. Thus the calculation is not carried out with parameters (displacement) directly measured in the test.

$$K_w 400 = \frac{2\int_{25mm}^{400mm} F(x)dx}{(400mm)^2 - (25mm)^2}$$

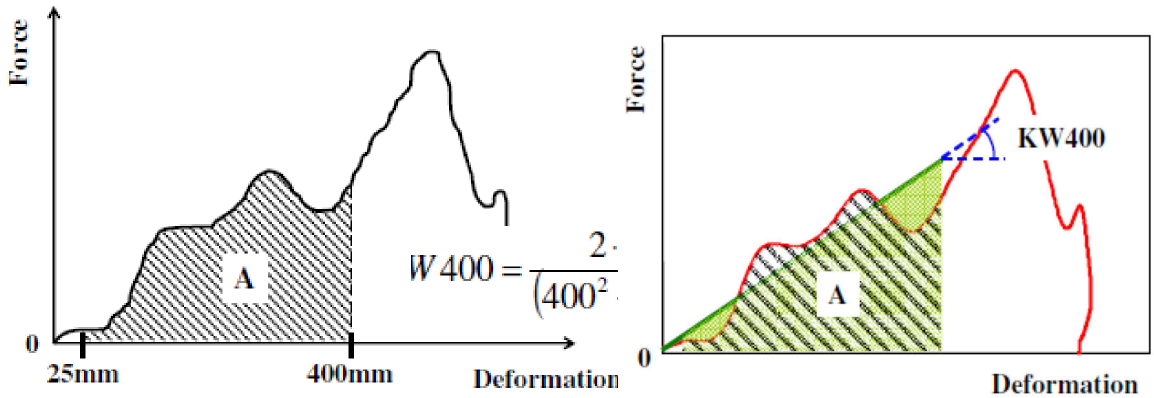


Figure 3.9: Energy calculation and KW 400 slope.

A fundamental issue with KW 400 is that the concept of this type of metric is that it should evaluate the amount of energy that the vehicle can absorb under a given force level, i.e. the passenger compartment strength of an impact partner. If the force deflection characteristic of the vehicle is assumed to be linear, then this is the case. This is because the energy absorbed by one vehicle under a given force level is inversely proportional to the KW 400 of the collision partner. Hence the ratio of the energy absorbed for two vehicles having a KW 400 of A and B is:

E_A/E_B = KW 400_B / KW 400_A

This means that in a vehicle-to-vehicle impact an impact partner (struck) vehicle will have to absorb more energy when the striking vehicle has a higher KW 400 as illustrated in Figure 3.10.

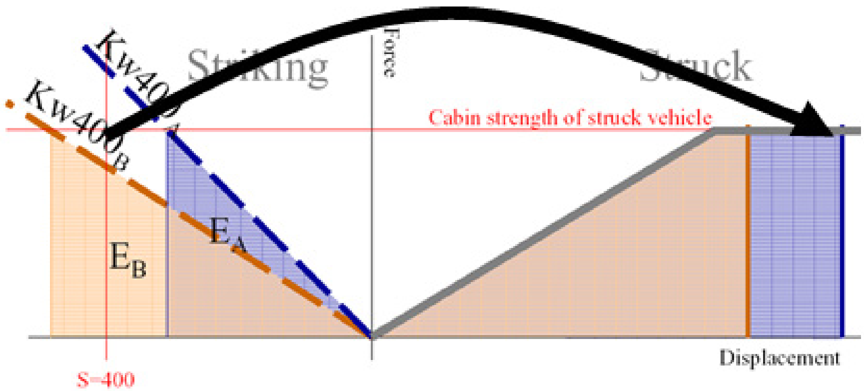


Figure 3.10: Force deflection plot showing that energy absorbed in vehicle-to-vehicle impact by struck vehicle is higher (blue area on right) when striking vehicle has higher KW 400 if it is assumed that vehicle has a linear force deflection relationship. Note: energy in striking vehicle A with high KW 400 above 'cabin strength of struck vehicle' is absorbed by struck vehicle (blue area on right).

However, in general, the force deflection characteristic of a vehicle is not linear and hence controlling the KW 400 does not necessarily control the energy absorbed under a given force level, i.e.

E_A/E_B (is not necessarily equal to) KW 400_B / KW 400_A

This means that a vehicle may have to absorb more impact energy (and hence be crushed more) when struck by a vehicle having a lower KW 400 as illustrated in Figure 3.11. This shows a fundamental issue with KW 400 and that, in principle, it is not suitable for its intended purpose.

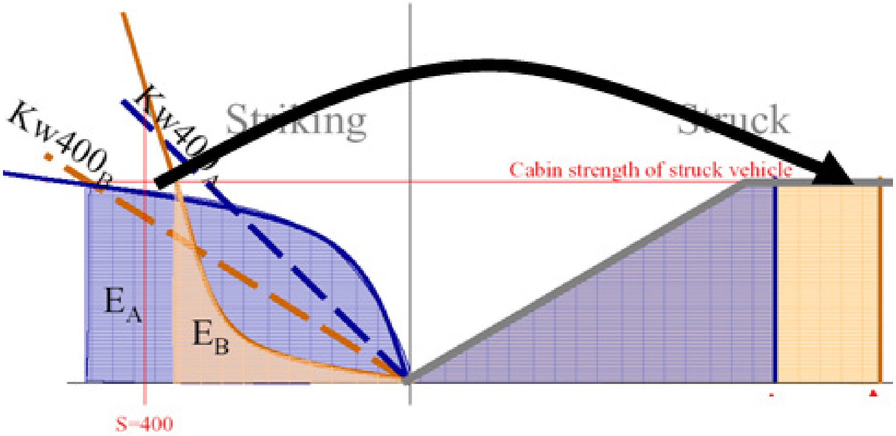


Figure 3.11: Force deflection plot showing that if a vehicle does not have a linear force deflection relationship then it is possible that energy absorbed in vehicle-to-vehicle impact by struck vehicle is higher (brown area on right) when striking vehicle has lower KW 400. Note: energy in striking vehicle B with low KW 400 above 'cabin strength of struck vehicle' is absorbed by struck vehicle (brown area on right).

Another issue with KW 400 was reported by Nissan [Hirayama 2007]. Their main point was that reducing the KW 400 of a vehicle will reduce its self protection if the vehicle deformation zone is not increased. This is because it would likely introduce a more "back loaded" crash pulse which is undesirable for the design of restraint systems and hence protection of occupants.

Other issues regarding KW 400 include that, as for the AHOF400 metric, this metric may not be suitable for the assessment of vehicles which have their SEAS in alignment with the common interaction zone. When a vehicle, such as an LTV, which has its SEAS in alignment with the common interaction zone, impacts a car, the LTV's PEAS will be loaded less than in a rigid barrier test because it will override the car's structure. As result, the effective stiffness of the LTV vehicle in the impact with the car will be substantially less than that measured in the rigid barrier test.

3.1.2.3 Force in a common interaction zone

Japan (Nagoya University) has proposed a metric to evaluate the height of a vehicle's PEAS based on the concept of force in a common interaction zone. The LCW 3rd (F3) and 4th (F4) row forces are measured when the total LCW force is 200 kN and the following performance limits applied to ensure that the PEAS align with the common interaction zone:

- F3+F4 ≥ 80 kN
- F4/(F3+F4) ≥ 0.2

- F4/(F3+F4) ≤ 0.8

The row forces are measured when the total LCW load is 200 kN so that the measurement is taken before the engine loads the wall. This ensures that the metric gives a measure of the height of the vehicle's crashworthy structures, i.e. its PEAS, and not its engine.

Issues with this metric include that, as for the AHOF400 metric, this metric may not be suitable for the assessment of vehicles which have their SEAS in alignment with the common interaction zone. Also, the metric is based on LCW row forces when the total LCW force is 200 kN. For some vehicles this is very early in the impact and hence the forces at this time may not be representative of the position of the vehicle's load carrying crash structures, i.e. PEAS. However, it should be noted that this metric has the advantage that it is very simple and easy to calculate.

3.1.2.4 Over-Ride Barrier (ORB) test

As mentioned above, in general, the Full Width Rigid Barrier (FWRB) test is not suitable for the assessment of a vehicle's structural interaction capability for vehicle's which have their SEAS in alignment with the common interaction zone. For this reason NHTSA proposed the use of a supplementary Over-Ride Barrier (ORB) test [Patel 2007, Patel 2009]. The idea was that vehicles with SEAS in alignment with the common interaction zone, which failed to meet the FWRB metric requirements, would be able to undergo an ORB test to properly assess their SEAS.

The Over-Ride Barrier consists of load cells which are mounted 500 mm from the instrumented back wall (Figure 3.12). The top of the ORB was infinitely adjustable to 16”–20” height (Part 581 zone) and was adjusted to be below the PEAS of the vehicle being tested. The vehicle is propelled into the barrier at a speed of 40 km/h and the force on the ORB measured. An initial proposal that a minimum force of 100 kN should be recorded before the vehicle has displaced 400 mm over the front of the barrier was made.

Figure 3.12: Over Ride Barrier (ORB).

NHTSA performed some ORB and vehicle-to-vehicle tests / simulations to verify the ORB test and proposed metric [Patel 2009]. The results for the Chevrolet Silverado were not encouraging. The Silverado has a bracket type SEAS (i.e. it consists of two brackets attached to each PEAS without a cross-member structure between them) which does not have a cross-member as shown in Figure 3.13.

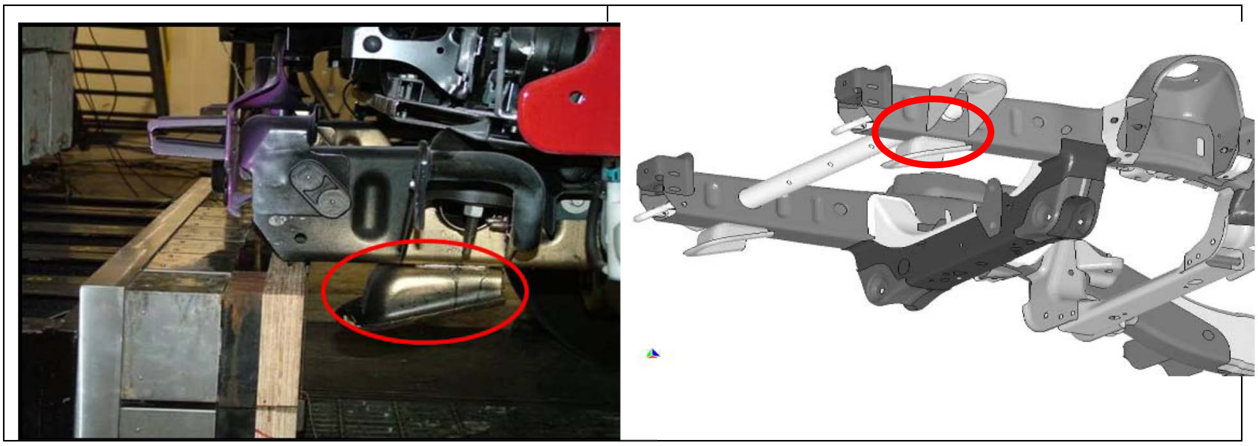


Figure 3.13: Chevrolet Silverado bracket type SEAS.

It was found that even though the SEAS met the 100 kN load requirement in the ORB test, simulations of 100 % overlap impacts between a Silverado and a Chrysler Neon with and without SEAS showed negligible effect on the overall crush kinematics of the Neon frontal structures. In contrast, a similar set of tests and simulations with the Ford F250, which had a SEAS with a cross-member structure, and a Chrysler Neon showed an improvement in the structural interaction with the SEAS present.

The results discussed above illustrate a possible problem with the ORB test, in that it may not detect crossbeam structures adequately. Further work is required to identify an appropriate ORB test procedure and performance limits. It may be the case that a deformable element in front of the ORB is required to detect SEAS crossbeam structures adequately. Also, additional criteria such as the energy absorbed may be required to ensure that the stiffness of the SEAS is controlled and they are not designed to be so strong that the collision partner is forced to absorb most of the impact energy.

3.2 Advantages / Disadvantages of FWDB and FWRB Tests

The advantages (disadvantages) of the FWDB and FWRB tests are as follows:

FWDB

- More representative of real world accident especially in initial stage of impact.
- More representative for initial deceleration of vehicle and loading of main rails which is important for sensing of crash for restraint system triggering.
- Engine dump loading attenuated, so can make assessment of vehicle structures that are relevant to crash that are loaded later in the impact, i.e. an assessment can be made of the vehicle’s main rails as opposed to its crush cans.
- Can assess SEAS structures, so no need for supplementary test, e.g. ORB.
- Possibly can assess horizontal structures (bumper beams).

FWRB

- Effectively already de-facto worldwide standard test so hence would be easier to introduce from harmonisation point of view.
- LCW measures vehicle forces directly, i.e. not filtered by deformable element.
- No problems with stability of deformable face or possibility of load spreading by deformable face.
- More test data available for development of metric

Note: Disadvantages of FWDB test are effectively advantages of FWRB test and vice versa for disadvantages of FWRB test.

In summary, the FWDB and FWRB tests both have advantages and disadvantages, but the FWDB has the edge technically because there is no need for a supplementary test and the assessment can be made later in the impact when it is more relevant. However, the FWRB is already a defacto worldwide standard test and hence has a large advantage from the harmonisation point of view.

3.3 Development of New / Revised Metrics

As described in Section 2 'Background', from a review of previous research, additional accident analysis and consultation with the GRSP Informal Group on Frontal Impact (GRSP IG FI), FIMCAR members have derived a strategy for the development of a set of test procedures to assess a vehicle's crash performance in frontal impacts. The first part of this strategy is that the set of test procedures should contain a full width test and an offset test. A full width test is required to provide a hard deceleration pulse to assess the restraint system. An offset test is required to assess the integrity of the occupant compartment and to provide a softer deceleration pulse to ensure that the restraint system performance is assessed for a variety of pulses.

As a first priority the tests should address structural interaction by improving the structural alignment of a vehicle's main crash structures and promoting good load spreading by vehicles having multiple load paths with strong connections between them. Based on previous research it was decided that the best way forward was to use the full width test with a LCW to assess a vehicle's structural alignment and the PDB offset test to assess a vehicle's load spreading capability. This approach was chosen because it was believed that it offered the best likelihood of success.

As a second priority, the tests should introduce force matching to ensure that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy using a full width and/or an offset test.

Hence, in summary for the full width test as a first priority it should be used to:

- Control structural alignment of a vehicle's main crash structures by using a LCW to detect that appropriate structures are in alignment with a common interaction zone.
- Provide a high passenger compartment deceleration pulse to provide a more severe test of the occupant restraint system. Note: It is intended that the offset test will provide a softer passenger compartment deceleration pulse, so that the restraint system is tested for a variety of pulses.

As a possible further step the full width test could be used to introduce force matching to ensure that in a vehicle-to-vehicle impact each vehicle absorbs its share of the impact energy

At this stage of the work, the advantages and disadvantages of both full width test procedures showed promising results (see also Section 3.2). Hence it was decided that metrics should be developed for both the FWDB and FWRB tests.

Based on the strategy and the review of the assessment criteria above the following objectives were formulated for the development of new / revised metrics for the FWDB and FWRB tests:

- Structural alignment (First priority)
  Metrics should be developed based on the 'force in a common interaction zone' concept. The 'common interaction zone' should align with the Part 581 zone used in the US voluntary commitment. The reason for this approach is to ensure that the metric developed aligns with assessments that are already used to aid harmonisation and to build on the most viable aspects of metrics previously developed.
  For the FWDB test, metric development should build on the 'force in a common interaction zone' metric described above. The reason for this is that this metric appears to offer a good chance of success based on the review above. It is expected that metric development will investigate issues such as, 'Up to what time in the impact the assessment should be performed?'.
  For the FWRB test, metric development should build on the 'force in a common interaction zone' metric proposed by Japan (Nagoya University). The reason for this is that, compared to the AHOF400 metric, this metric follows the concept of 'force in a common interaction zone' more closely and makes an assessment early in the impact (before engine dump loading) and hence should give a better assessment of the position of the vehicle's structures. It should be noted that for the FWRB test it may be necessary to develop further the ORB test, or an equivalent test, for the assessment of vehicles which have SEAS in alignment with the common interaction zone.
- Force matching (Second priority)
  The review above shows that the KW 400 metric has a fundamental issue and that, in principle, it is not suitable for the control of force matching. Hence, development of new metrics should be investigated which are better linked to the vehicle's force levels. It is proposed that initial effort is concentrated on the FWRB test because this barrier face does not have the added complications of a deformable element which modifies force levels and absorbs energy.

Metrics developed should be kept as simple as possible so that their purpose and how they work can be understood easily. This should make them easier to accept.

The remainder of this section is divided into four parts. The first describes the test data available for development of the metrics. The second part describes the development of metrics to control a vehicle's structural alignment and the third development of metric concepts to control a vehicle's force matching. The final part is the discussion and conclusions.

3.3.1 Test Data

For the development of a new / revised metric, crash test data for a range of vehicles which should and should not meet the metric requirements was needed. This is mainly to be able to try different solutions and determine the best one. Test data from previous European projects and tests performed in other countries were collected. These data were then arranged into the appropriate format and imported into the FIMCAR test data base.

FWDB test data were obtained mainly from previous European projects such as VC-Compat and APROSYS, as this type of test is a research test. However, the Japanese government also provided some data for FIMCAR to use. FIMCAR gratefully acknowledges the provision of these data by Japan which were provided through a project collaboration. Table 1 shows an overview of the test data collected. It should be noted that the ground clearance of the bottom of the LCW was not the same for all tests. The current standard for ground clearance is 80 mm. To be able to use the results from tests which did not have a ground clearance of 80 mm, it was assumed that they were equivalent to a test with the same vehicle but with a changed ride height to account for the difference in ground clearance. For example, a test performed with a vehicle with a barrier ground clearance of 50 mm was assumed to be the same as a test performed with a barrier clearance of 80 mm with the vehicle's ride height increased by 30 mm.

Table 2: Overview of test data for the development of FWDB metric.

Vehicle	Vehicle size	Source	LCW ground clearance (mm)
Wagon R	Japanese mini-car	Japan	125
Smart	Supermini	VC-Compat	50
Fiesta	Supermini	APROSYS	80
Panda	Supermini	VC-Compat	80
Micra	Supermini	APROSYS	80
Golf IV	Small Family	BASt	50
Golf V	Small Family	VC-Compat	80
Astra MY2004 (x2)	Small Family	VC-Compat / DfT	80
Bravo (x2)	Small Family	APROSYS	80
Focus	Small Family	DfT	50
Rover 75 (x3)*	Large family	ACEA	50
Laguna II	Large family	VC-Compat	50
E-Class	Executive	VC-Compat	50
CR-V	Small SUV	VC-Compat	50
Touareg	Large SUV	VC-Compat	80
XC90	Large SUV	VC-Compat	50

*Bumper crossbeam strength was changed between tests (weak, standard, strong)

FWRB test data were obtained from a variety of sources as this test is performed more widely than the FWDB test because a rigid barrier test is a mandatory test procedure in many parts of the world. In many consumer and regulatory rigid barrier tests LCW data is collected for research purposes. The FWRB collected included many crash tests which were performed within the Japanese NCAP test programme. In total 82 crash tests with the rigid barrier and the load cell wall measures were supplied by Japan (n = 19 from 2005; n = 18 from 2006; n = 15 from 2007; n = 18 from 2008; n = 12 from 2009). Additionally test data from NHTSA (n = 15) were available which helped to complement the crash test data in regard to another world wide market. FWRB data sets for three further vehicles were available from previous European projects.

3.3.2 Structural Alignment

As mentioned above the overall objective of the work was to develop new / revised metrics for the FWDB and FWRB tests to control structural alignment of a vehicle's main crash structure by using an LCW to detect that appropriate structures are in alignment with a common interaction zone.

The common interaction zone should be based on the Part 581 zone to ensure harmonisation with the US voluntary commitment Section 3.1.1 'Full Width Deformable Barrier (FWDB)', 'Force in a common interaction zone metric'. The common interaction zone was chosen to be LCW Rows 3 and 4 which is centred on the centre of the Part 581 zone and encompasses it (Figure 3.14). This means that a minimum load requirement in Rows 3 and 4 ensures that the vehicle has loaded the wall in a manner which spans the Part 581 zone, i.e. a load requirement for Row 3 ensures that load is applied to the bottom half of the Part 581 zone or just below it and similarly a load requirement for Row 4 ensures that load is applied to the top half of the Part 581 zone or just above it.

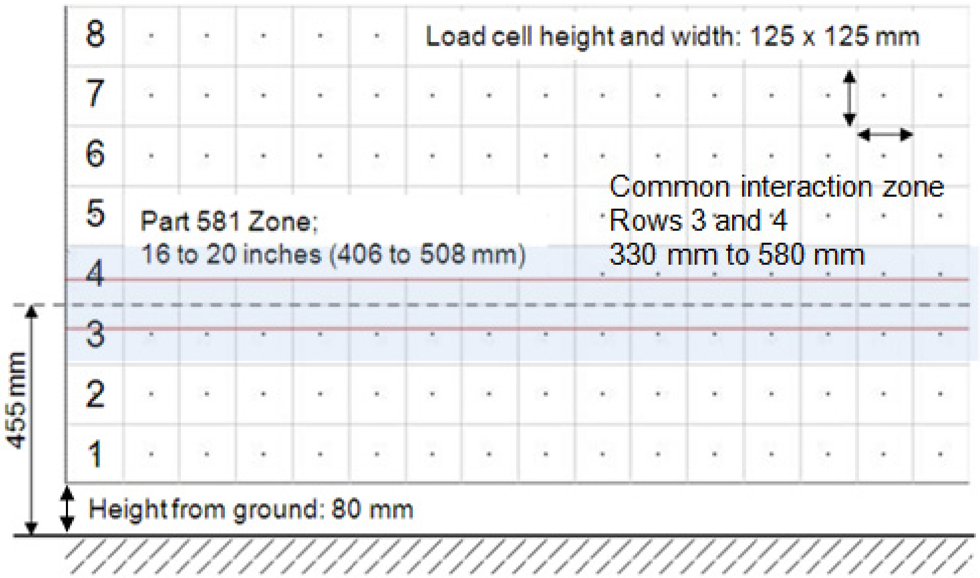


Figure 3.14: Alignment of Part 581 zone and 'common interaction zone' with LCW.

Another objective for development of the metric for structural alignment is that it should not discourage the design of vehicles that spread their load better by using multiple load paths, e.g. an engine subframe load path, and if possible encourage this type of design. The reason for this is to ensure that there are no conflicts between the requirements for structural alignment and those for load spreading, both of which are needed for good structural interaction.

The methodology followed to develop the metrics was to investigate how modifications to the metrics affected the assessment of the vehicle using the metric compared to a geometric assessment of the vehicle based on the US voluntary commitment. The aim was to achieve a 100 % correlation between the metric assessment and the geometric assessment unless a suitable explanation could be found of why they should not correlate.

The US voluntary commitment states that all LTVs sold by participating manufacturers in the US should fulfil one of the options below:

OPTION 1

The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone (Option 1a)

AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2

If a light truck does not meet the criteria of Option 1, there must be a secondary energy absorbing structure (SEAS), connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone.

Based on this a geometric assessment of the vehicles was made with minor modifications compared to the US voluntary agreement for the options below as shown in Figure 3.5:

- Option 1a a/b ≥ 50%
- Option 1b a/c ≥ 50%
- Option 2 For vehicles which do not meet Option1a or b, are there SEAS in Part 581 zone?

It should be noted that for all the work performed the LCW data was filtered using a CFC60 filter for the output of each cell.

3.3.2.1 Development of metrics for FWDB

Starting from the ‘Force in a common interaction zone’ metric described in the ‘Review of current and previous assessment criteria’, Section 3.1.1.3, three candidate metrics were developed which are summarised in Figure 3.15.

Many metric variations were investigated and the most promising chosen based on the correlation of the metric assessment of the test vehicles with the geometrical assessment based on the US voluntary commitment as described above. Also stakeholders, such as the GRSP Informal Group on Frontal Impact were consulted to help determine which metrics were the best. In addition, feedback received from other stakeholders attended the first FIMCAR workshop to discuss the different options was considered.

The development process involved consideration of issues such as:

- Up to what stage of the impact should the assessment be made? Good structural interaction is important throughout the whole of the impact. To achieve this, ideally the structures should be in alignment from the beginning to the end of the impact. However, the offset test with the PDB can only assess the structural interaction potential of a vehicle at the end of the impact because the assessment is based on a barrier deformation measure. Hence, it was decided that the FWDB test should make an assessment earlier in the impact so that the procedures proposed by FIMCAR assess structural interaction at two points in time; towards the beginning of the impact and at the end of the impact.
- Should the metric consist of one or two stages and if it has two stages should it have an eligibility assessment to determine whether or not the vehicle should be allowed to undergo the second stage? It should be noted that feedback from the GRSP IG FI said that, if possible, they would prefer not to have an eligibility assessment and if one was required then it should not be based on vehicle category type.

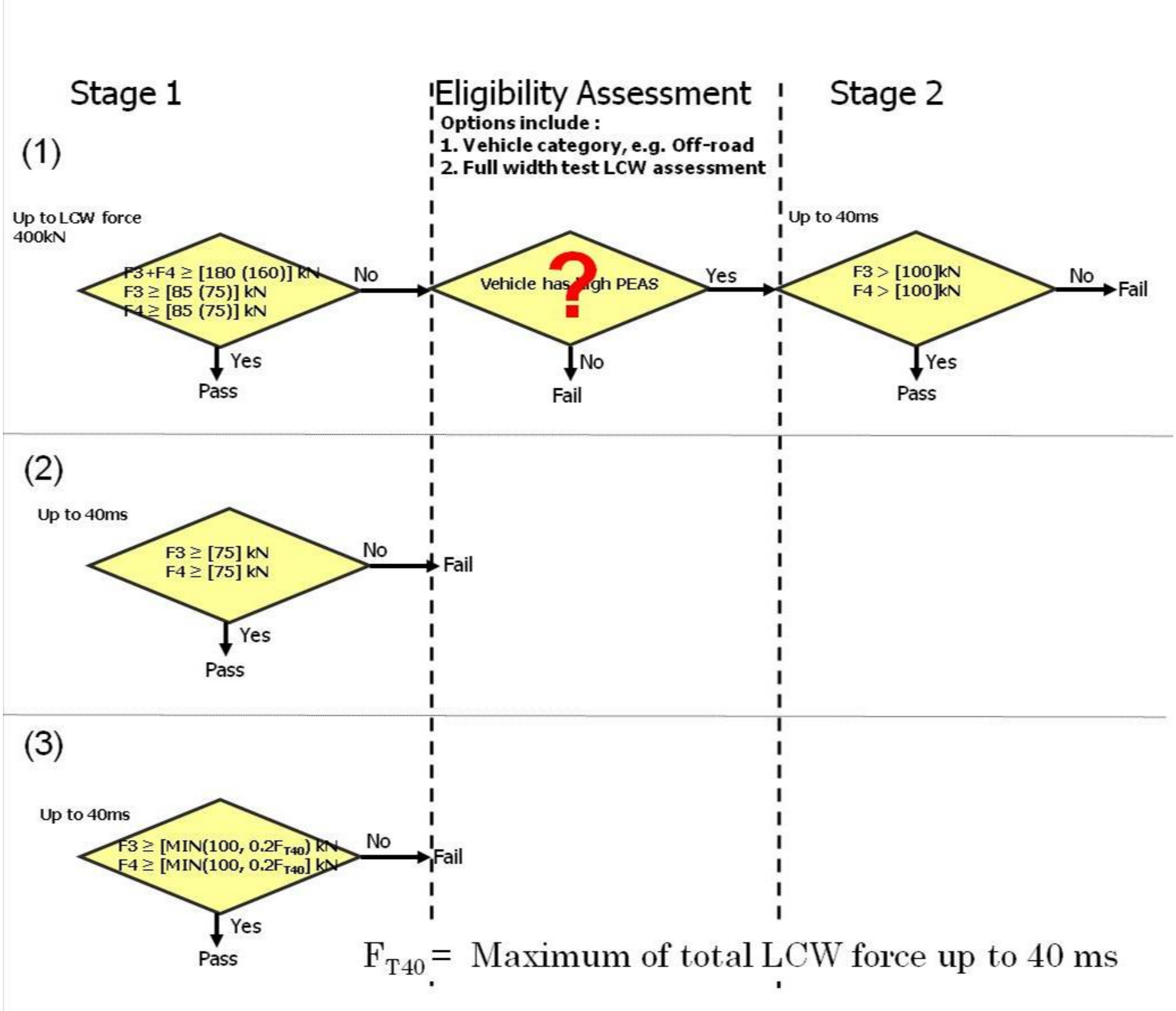


Figure 3.15: Proposed metric candidates for FWDB test.

FWDB metric (1)

This metric candidate consists of two stages with a possible eligibility assessment. The idea is that the first stage should assess whether the vehicle's PEAS align with the common interaction zone. If they do not, then the second stage should assess whether the vehicle has an adequate SEAS in alignment with the common interaction zone. A possible eligibility assessment could be used to ensure that only certain vehicles, for example those which require a high PEAS, such as offroad vehicles to achieve a high approach angle, would be allowed the concession of the second stage.

For the first stage an assessment up to the point in the impact when the LCW total force first reaches 400 kN is made. The value of 400 kN was chosen because:

- At this point in the impact the vehicle's crash structures are loaded fully and hence their characteristics can be assessed properly.
- The metric assessment correlated better with the geometric assessment compared with an assessment made earlier in the impact, e.g. 200 kN or 300 kN.

Performance requirements proposed are:

$$F3+F4 \geq [180] \text{ kN}$$

$F3 \geq [85]$ kN

$F4 \geq [85]$ kN

where F3 and F4 are the maximum of the load on Row 3 and Row 4 up to the time in the impact when the LCW total force first reaches 400 kN.

For vehicles for which the LCW total force does not reach 400 kN (which is possible for light cars) a concession is made; the performance requirements are reduced as below:

$F3+F4 \geq [160]$ kN compared with 180 kN

$F3 \geq [75]$ kN compared with 85 kN

$F4 \geq [75]$ kN compared with 85 kN

where F3 and F4 are the maximum of the load on Row 3 and Row 4 up to the time in the impact when the LCW total force reaches its maximum. At present this concession is implemented in a step wise fashion. At a later date, if this candidate metric is adopted, it may be necessary to change this to a sliding scale based on the difference between the maximum LCW total force and 400 kN.

The possibility of including an eligibility assessment for stage 2 is included. The concept is to only allow certain types of vehicles (i.e. those with a high PEAS) to be able to proceed to stage 2. Stage 2 assesses if the vehicle has an adequate SEAS in alignment with the common interaction zone (Part 581 zone). An eligibility assessment could be based either on the vehicle category, e.g. Off-road vehicle (Category G as defined in the framework Directive), or an LCW assessment. An LCW assessment has been developed which is based on a minimum requirement for the loads in the early part of the impact (up to time when LCW total force equals 200 kN) on the upper part of the LCW (rows 4 and 5). The concept is that this should detect vehicles which have high PEAS in alignment with Rows 4 and 5. The proposed performance requirement is that the total of the loads on Rows 4 and 5 should be greater than 100 kN. However, it should be noted that during consultation the GRSP Informal Group on Frontal Impact informed FIMCAR that an eligibility assessment was undesirable and that it should be avoided if possible. They said that ideally all vehicles should be subjected to the same test and performance requirements. The majority of the FIMCAR consortium came to the same conclusion.

For the second stage an assessment is made up to 40 ms into the impact. This time was chosen because it should be sufficient to allow the detection of SEAS positioned up to 400 mm rearwards of the front of the vehicle. This has been explained previously in Section 3.1.1 'Review of Structural Interaction Criterion'. Performance requirements proposed are:

$F3 \geq [100]$ kN

$F4 \geq [100]$ kN

The correlation of this metric with a geometrical assessment of vehicle's structures based on the US voluntary commitment is shown below (Figure 3.16). The top part of the figure shows the geometric assessment of the vehicle's structures as described in Figure 3.5. The bottom part of the figure shows the assessment of the vehicle using the metric. It should be noted that some vehicles are labelled with a measurement attached, e.g. SMART +30 mm. This is to indicate that the ride heights of these vehicles have been adjusted to account for the fact that the test was performed with a different LCW ground clearance to the standard of 80 mm. For example, the SMART test was performed with a LCW ground clearance of 50 mm which is equivalent to performing a test with the SMART with a ride height increase of 30 mm and a LCW with a ground clearance of 80 mm, i.e. both the car and the wall have been raised by 30 mm. It is seen that there is good agreement between the geometric assessment and the metric for all vehicles expect those circled in red, namely Rover 75 (ride height raised), VW Touareg, and Volvo XC90 (ride height raised). For the Rover 75, the subframe structure was not assessed consistently by the metric for all the vehicles tested (Note: the three vehicles had different bumper beam structures). However, it is debatable whether this was an adequate subframe structure because of its small frontal area and hence whether it should be assessed as adequate or not. For the VW Touareg the PEAS was not detected by the metric 1st stage even though it aligned with Row 3 and Row 4. This could have been caused by movement of the rails during the crash, the design of the front of the rails and bumper beam preventing the full height of the rail interacting with the wall or errors in the measurements of the heights of the vehicle's structures. For the Volvo XC90 with a ride height increase of 30 mm the SEAS was not judged adequate by the metric. However, it is not known whether or not the XC90 SEAS in this configuration is adequate or not and hence it is not known definitely whether or not the metric assessment is correct or not. In short it is probably a borderline case.

	Smart + 30mm	Fiesta	Panda	Micra	Golf IV + 30mm	Golf V	Astra	Astra	Bravo	Bravo	Focus +30mm	Focus – 32.5mm	Focus + 92.5mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Rover 75 + 30 mm	Laguna II + 30mm	E-Class + 30mm	CR-V + 30mm	Touareg	XC90 + 30mm	Wagon R – 45 mm
Option 1a	89.4	99.6	91.1	57.1	97.0	84.6	71.5		62.0		34.4	88.2	0.0	55.1			56.1	100	19.1	70.7	0.0	11.8
Option 1b	95.0	93.5	83.4	64.4	89.6	94.3	70.8		84.0		34.6	88.8	0.0	44.1			57.0	67.9	19.7	74.4	0.0	7.1
Option 2														?							?	
F3+F4 ≥ 180kN (160 kN) upto 400kN	177	268	223	196	219	236	237	243	225	222	199	241	185	253	251	227	246	226	227	267	172	157
F3 ≥ 85kN (75kN) upto 400kN	105	134	107	98	102	150	89	93	92	94	65	150	35	69	48	73	97	98	81	37	36	108
F4 ≥ 85kN (75 kN) upto 400 kN	79	134	116	98	155	89	148	150	133	129	155	91	150	184	203	163	172	128	146	237	151	49
F3 ≥ 100kN upto 40 ms	105	175	133	134	102	150	127	142	121	119	65	150	35	116	88	84	117	154	179	132	85	139
F4 ≥ 100kN upto 40 ms	79	166	140	98	123	105	182	179	167	162	149	95	150	248	301	255	172	171	235	320	295	55

Figure 3.16: Correlation of FWDB (1) metric with geometrical assessment of vehicle's structures based on the US voluntary commitment showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail

overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.

2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB (1) metric consists of two stages. The values of the metric for stage 1 for (F3+F4), F4, and F3 are noted in the top three rows of the metric assessment and the values of the metric for stage 2 for F4 and F3 are noted in the bottom two rows. Whether or not the performance limit is met is indicated in green (met) and red (not met). Please note that if stage 1 of the metric is met stage 2 does not have to be met as well. Hence, the 'Focus – 35 mm' meets the metric requirements because it passes stage 1 even though it does not pass stage 2.

FWDB metric (2)

This metric candidate consists of one stage which assesses all of the vehicle's structures, i.e. PEAS and SEAS. The assessment is made up to 40 ms into the impact to enable the detection of structures up to 400 mm rearward of the front of the vehicle, as with stage 2 of the FWDB (1) metric. Performance requirements proposed are:

F3 ≥ [75] kN

F4 ≥ [75] kN

The correlation of this metric with a geometrical assessment of vehicle's structures is shown below (Figure 3.17). The agreement is very good; all vehicles which pass the geometric assessment meet the metric requirements and all those which do not pass the geometric requirements do not. For the Rover 75 (increased ride height) and XC90 (increased ride height) the metric requirement is met even though it is debatable whether or not they should meet the requirements.

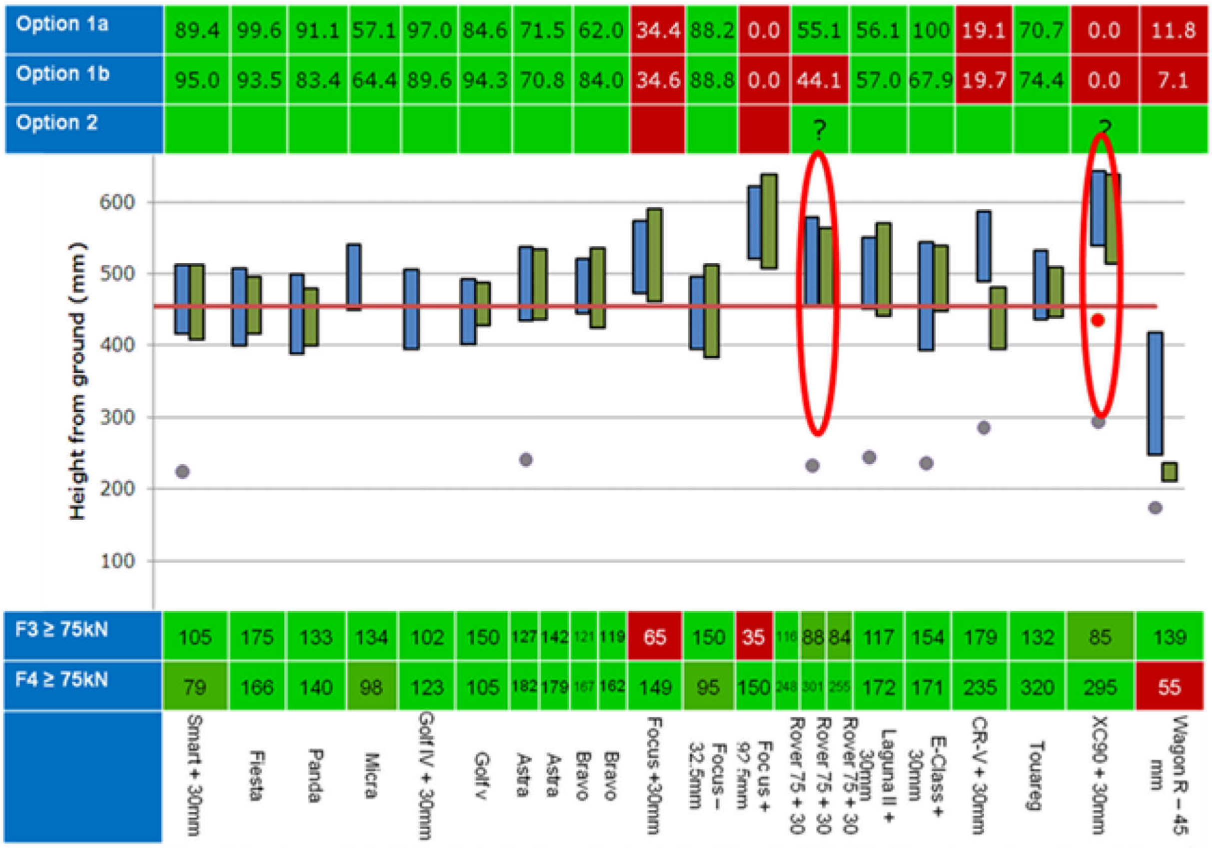


Figure 3.17: Correlation of FWDB (2) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.
2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB (2) metric consists of one stage. The values of the metric for stage 1 for F4, and F3 are noted in the two rows of the metric assessment. Whether or not the performance limit is met is indicated in green (met) and red (not met).

It should be noted that the main reason the requirement was set at 75 kN was to ensure that the SMART car could meet the requirement because the geometric assessment showed that it should. However, it is debatable that a requirement of 75 kN is high enough to ensure an adequate SEAS on larger vehicles for whom 75 kN is a much lower proportion of the total load on the wall (total LCW force max up to 40 ms SMART 370 kN, XC90 = 800 kN). For this reason the FWDB (3) metric was developed.

FWDB (3)

As for FWDB metric 2, this metric candidate consists of one stage which assesses all of the vehicle's structures and the assessment is made up to 40 ms into the impact to enable the detection of structures up to 400 mm rearward of the front of the vehicle. The concept of the metric is to ensure realistic load requirements for both heavy and light vehicles. This is achieved by using a row load requirement of 100 kN for heavy vehicles and a requirement of a proportion of the total LCW force for light vehicles. The performance requirements are:

$$F3 \geq [\mathrm{MIN}(100, 0.2F_{T40}) \text{ kN}$$

$$F4 \geq [\mathrm{MIN}(100, 0.2F_{T40}] \text{ kN}$$

where F_{T40} = Maximum of total LCW force up to time of 40 msec

The correlation of this metric with a geometrical assessment of vehicle's structures is shown below (Figure 3.18). Agreement is good, but now the Rover 75 (increased ride height) and XC90 (increased ride height) fail to meet the requirements, the opposite result to the FWDB metric (2) assessment.

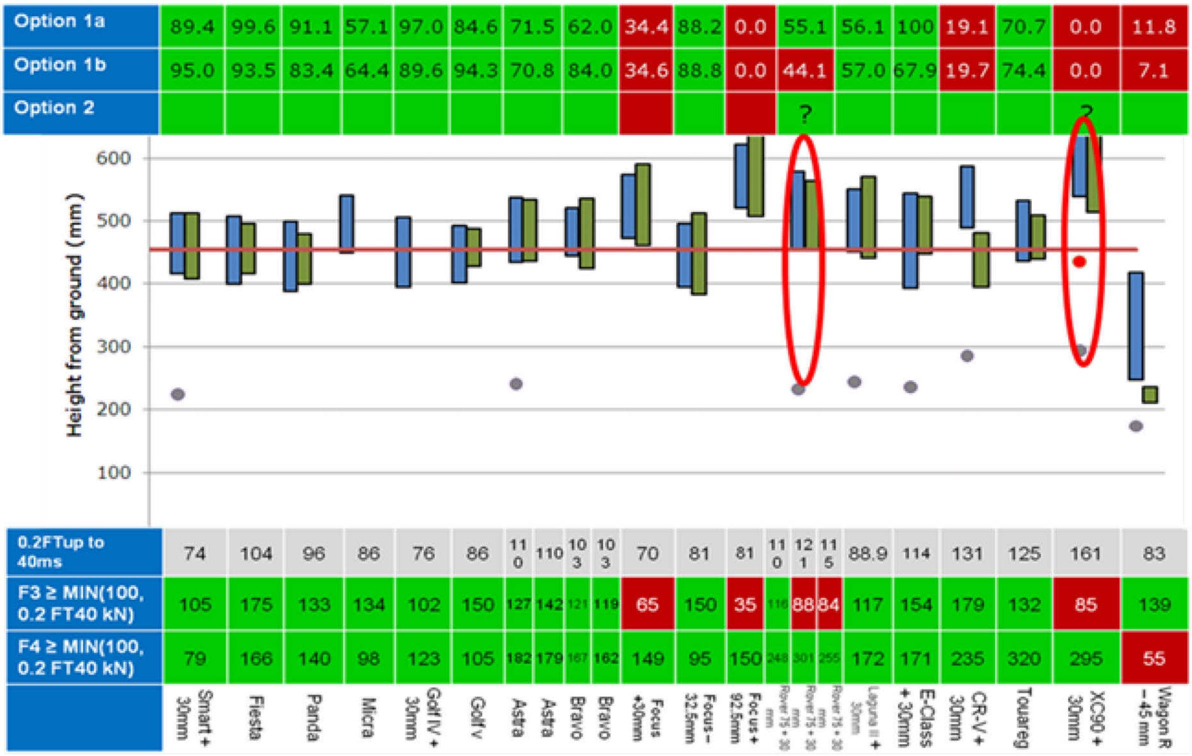


Figure 3.18: Correlation of FWDB metric (2) with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.

Notes:

1. For the geometric assessment; Option 1a shows what percentage of the Part 581 zone the rail overlaps (≥ 50% to pass), Option 1b shows what percentage of the rail overlaps the Part 581 zone (≥ 50% to pass) and Option 2 shows if the vehicles has a SEAS which extends to at least the bottom of the PART 581 zone. Whether or not the requirement is met is indicated in green (met) and red (not met). Please note that if Option 1a and 1b are met Option 2 does not have to be met as well. Also, note that Honda CRV meets Option 2 SEAS requirement with bumper crossbeam.

2. The blue bars show the height above ground of the vehicle's PEAS (main longitudinals) and the green bars the height of vehicle's bumper beam. The grey dots indicate the approximate position of the vehicle's subframe if it has one.
3. The FWDB metric (3) consists of one stage. The values of the metric for stage 1 for F4, and F3 are noted in the bottom two rows of the metric assessment. Whether or not the performance limit is met is indicated in green (met) and red (not met).

Discussion and Conclusions

Three metrics have been developed for the FWDB test. One of these has two stages with a possible eligibility assessment for the second stage and the other two have one stage only. In the spirit of keeping the metric as simple as possible and because the correlation of the metrics with the geometric assessment is similar, it is believed that a single stage metric is the better way forward. Of the two single stage metrics it is believed that the FWDB (3) metric is the better candidate because effectively it allows the mass of the vehicle to be taken into account in the performance requirement.

3.3.2.2 Development of Metrics for FWRB

Starting from the 'Force in a common interaction zone' metric developed by Japan (Nagoya University) described in the 'Review of current and previous assessment criteria', Section 3.1.2.3, three candidate metrics were developed. These are summarised in Figure 3.19.

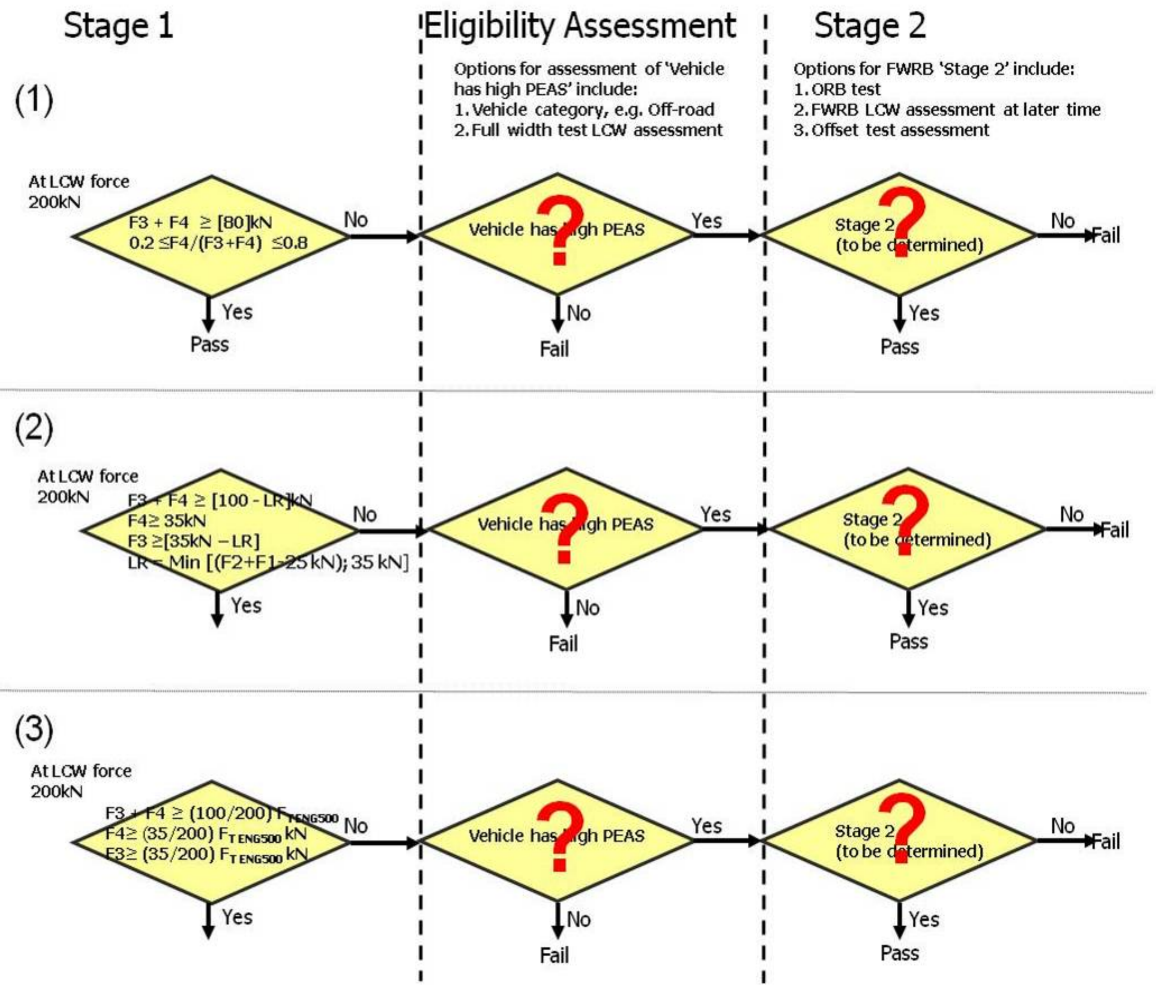


Figure 3.19: Proposed metric candidates for FWRB test.

As for the FWDB test, many metric variations were investigated and the most promising chosen based on the correlation of the metric assessment of the test vehicles with the geometrical assessment based on the US voluntary commitment as described above. Also stakeholders, such as the GRSP Informal Group on Frontal Impact and experts at the FIMCAR workshop were consulted to help determine which metrics were the best.

The development process involved consideration of the following issues:

- At what stage in the impact should the assessment be made up to?
  It was found that an assessment based on the 'force in a common interaction zone' concept could only be made before 'engine dump' loading occurred, i.e. the rapid deceleration of the engine caused by direct or indirect contact with the LCW. This was because in a rigid barrier test the loads applied by the engine to the LCW may not be representative of those applied in a car-to-car impact. In turn, this is because the loads applied by the engine in the rigid wall test can be very localised and high because of rigid features on the engine, such as the alternator, interacting with the rigid wall and causing the engine to come to an abrupt halt. In contrast in an impact with another vehicle the engine is less likely to come to such an abrupt halt because the other vehicle will be more compliant and not behave in such a rigid manner, e.g. the engine of a partner vehicle may move and rotate.
- Should the metric consist of one or two stages and if it has two stages should it have an eligibility assessment to determine whether or not the vehicle should be allowed to undergo the second stage?
- Should vehicles that have load paths positioned below the common interaction zone which improve their structural interaction potential be allowed concessions to ensure that they are not discouraged and possibly encouraged?

<u>FWRB Metric (1)</u>

This metric candidate is based on the proposal made by Japan (Nagoya University) described in Section 3.1.2.3 which in turn is based on the 'Force in a common interaction zone' concept. It should be noted that the development of this metric was supported by Japan (Nagoya University and JARI) and this is gratefully acknowledged. The metric consists of a Stage 1 and possibly a Stage 2 with a possible eligibility assessment. The Stage 1 of the metric is described below followed by a discussion of a possible Stage 2 and a possible eligibility assessment.

Stage 1 of the metric effectively assesses the height of the vehicle's PEAS. The LCW 3rd (F3) and 4th (F4) row forces maximums are measured at the time when the total LCW force is 200 kN. The following performance limits are applied to ensure that the PEAS align with the common interaction zone:

- $F3+F4 \geq 80$ kN
- $F4/(F3+F4) \geq 0.2$
- $F4/(F3+F4) \leq 0.8$

The reason why the row forces are measured at the time when the total LCW load is 200 kN is so that the measurement is taken before the engine loads the wall as shown in Figure 3.20. This ensures that the metric gives a measure of the height of the vehicle's structures, i.e. its PEAS, and not its engine. Also, because the row load forces are assessed when the total LCW force is a fixed magnitude (200 kN), it is effectively normalised. This helps to ensure that the metric is independent of the mass of the vehicle and assesses the vehicle's structural interaction potential only.

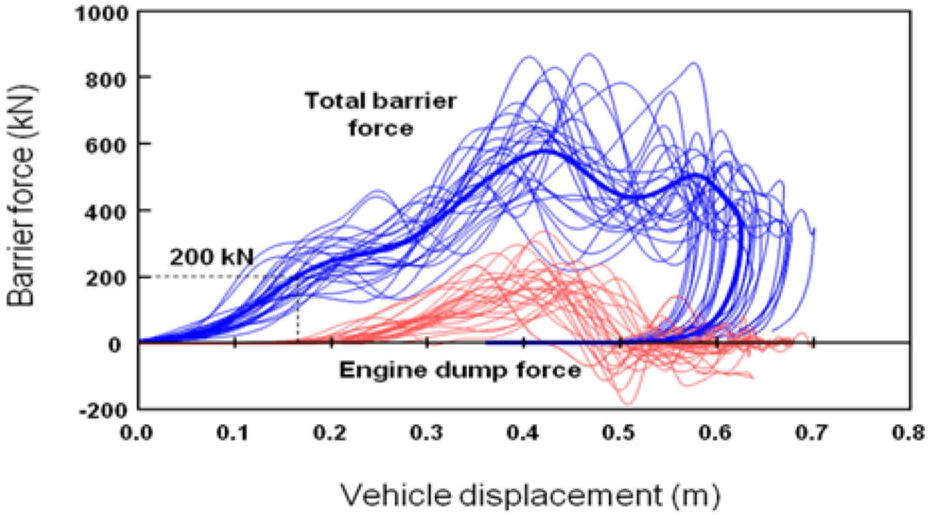


Figure 3.20: Total barrier force and engine dump force showing engine dump loading does not occur before total barrier force is greater than 200 kN. Data JNCAP 2007-2008 excluding Japanese minicars[1].

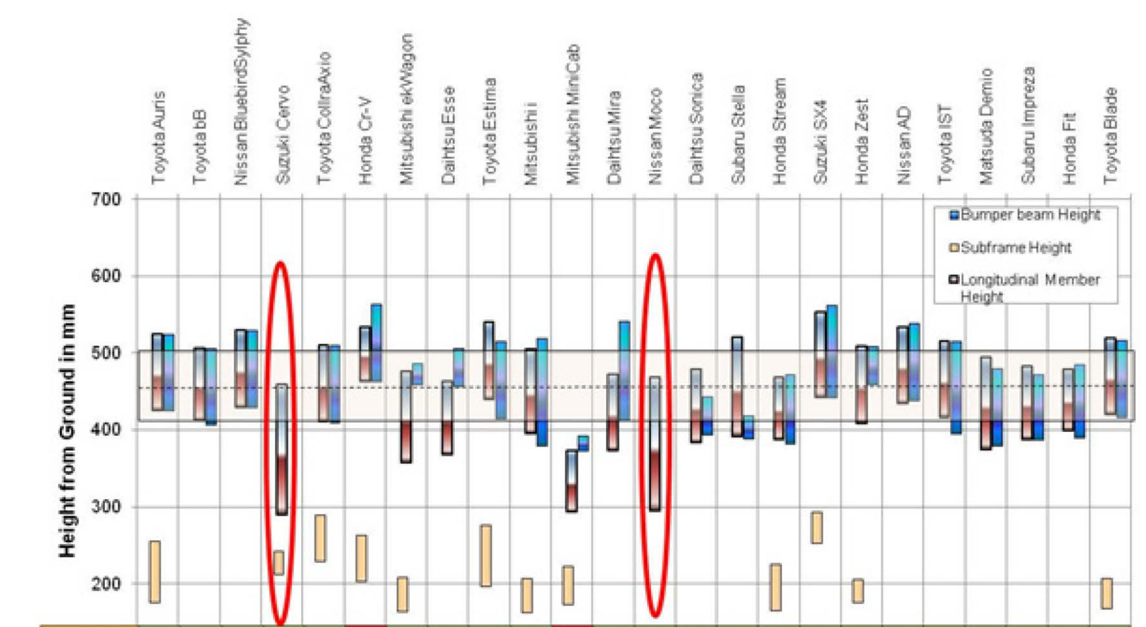
The correlation of this metric with a geometrical assessment of vehicle's structures based on the US voluntary commitment is shown below (Figure 3.21 and Figure 3.22). The top part of the table shows the result of a geometric assessment of the vehicle's structures as described in Figure 3.5, i.e. Option 1a the vehicle's PEAS overlap at least 50% of the Part 581 zone; Option1b at least 50% of the vehicle's PEAS overlap the Part 581 zone. The bottom part of the table shows the result of the metric assessment of the vehicle. It is seen that the geometric and metric assessments correlate for all vehicles except those circled in red. Reasons why the assessments do not correlate for these vehicles are discussed further below:

- Suzuki Cervo and Nissan Moco
  These vehicles do not fulfil Option 1b of the geometric assessment because their PEAS have a particularly tall cross-sectional height and hence 50% of their PEAS do not overlap the Part 581 zone. Whether or not these PEAS should be assessed as sufficient is a debatable point. It can be argued that the PEAS have a tall cross-sectional height which spreads the load and helps to offer good structural interaction, hence they should be assessed as sufficient. Alternatively, it can be argued that the PEAS do not put sufficient load into the top half of the Part 581 zone (Row 4 about 25 kN) and should be assessed as insufficient. This is because in an impact with a high SUV type vehicle which has structures mainly in alignment with the top half of the Part 581 zone (Row 4) it could be overridden. The authors concur with the latter point and believe that it is important that a specified minimum load is applied to Row 4 to ensure the vehicle has sufficient structure in alignment with the

[1] Japanese minicars are restricted in external dimensions (i.e., l < 3.39 m; w < 1.475 m) and engine size < 660 cm³ and offer the advantage of lower tax. In ordert o fulfil the external dimension restrictions while offering a maximum internal space the front end design is considerably different to standard cars (i.e., often without crash box and cross member

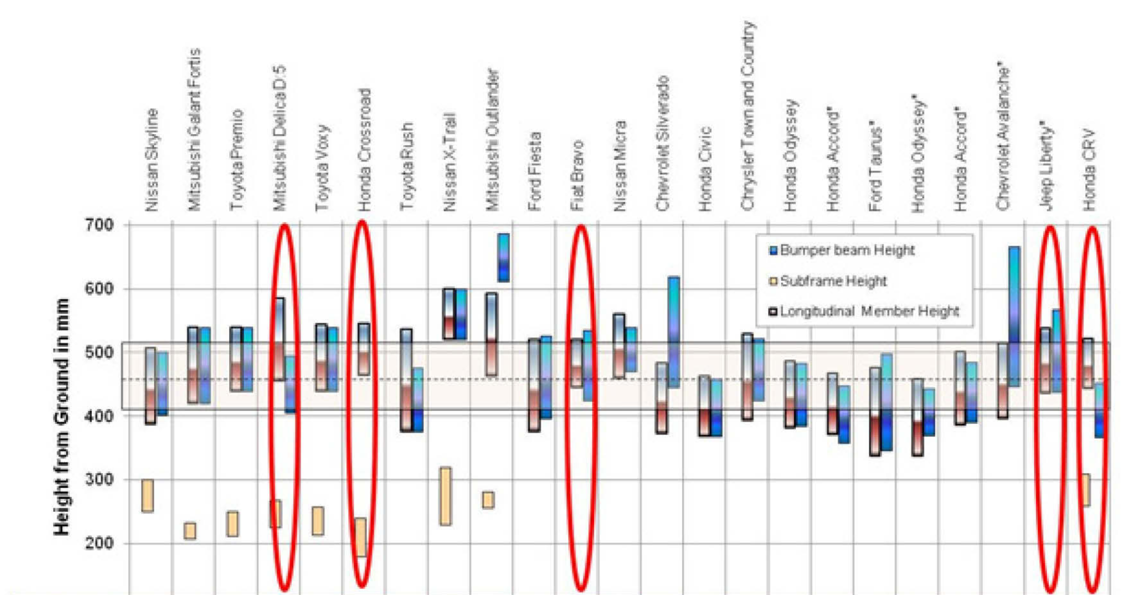
top half of the Part 581 zone. This is one of the reasons for the development of FWRB metric (2) which is based on the specification of minimum row loads.

- Mitsubishi Delica
  This vehicle was assessed as borderline for both the geometric assessment and the metric assessment. Hence it is unclear whether this vehicle should be assessed as sufficient or not.
- Honda Crossroad
  Further examination of the test data found that the impact accuracy for this test was z = -11 mm. This is sufficient to explain why the vehicle failed the geometric assessment but passed the metric assessment. The vehicle was 11 mm lower in the test than for the geometric assessment and hence its PEAS (longitudinals) had a greater overlap of the Part 581 zone.
- Fiat Bravo
  This vehicle met the geometric assessment but failed to meet the metric assessment because it did not apply a large enough load to Row 3. A possible explanation for this discrepancy could be the impact accuracy in the test; the vehicle may have impacted high leading to lower loads on Row 3. Unfortunately impact accuracy was not recorded in the test.
- Jeep Liberty
  Again the explanation for this discrepancy may be impact accuracy. This is not known for this test.
- Honda CRV
  The most likely explanation for this discrepancy for this test is the position of the crush cans on the Honda CRV. They are positioned in alignment with Row 4 and hence would result in most of the load from the PEAS (longitudinals) being applied to Row 4 in the initial stages of the impact before the LCW total force reached 200 kN even though the longitudinals actually overlap Row 3.



	Toyota Auris	Toyota bB	Nissan BluebirdSylphy	Suzuki Cervo	Toyota CollraAxio	Honda Cr-V	Mitsubishi ekWagon	Daihtsu Esse	Toyota Estima	Mitsubishi i	Mitsubishi MiniCab	Daihtsu Mira	Nissan Moco	Daihtsu Sonica	Subaru Stella	Honda Stream	Suzuki SX4	Honda Zest	Nissan AD	Toyota IST	Matsuda Demio	Subaru Impreza	Honda Fit	Toyota Blade
Option 1a	1	1	1	1	1	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
Option 1b	1	1	1	0	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
F3+F4≥80	167	147	155	87	149	167	138	155	153	176	73	157	86	148	126	143	97	130	151	168	160	149	152	155
0.2≤F4/(F3+F4)≤0.8	0.54	0.51	0.77	0.31	0.57	0.93	0.3	0.38	0.71	0.52	0.25	0.31	0.25	0.59	0.47	0.31	0.7	0.52	0.65	0.64	0.46	0.37	0.24	0.47

Figure 3.21: Correlation of FWRB (1) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red.



	Nissan Skyline	Mitsubishi Galant Fortis	Toyota Premio	Mitsubishi Delica D:5	Toyota Voxy	Honda Crossroad	Toyota Rush	Nissan X-Trail	Mitsubishi Outlander	Ford Fiesta	Fiat Bravo	Nissan Micra	Chevrolet Silverado	Honda Civic	Chrysler Town and Country	Honda Odyssey	Honda Accord*	Ford Taurus*	Honda Odyssey*	Honda Accord*	Chevrolet Avalanche*	Jeep Liberty*	Honda CRV
Option 1a	1	1	1	1	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1
Option 1b	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	1	1	1	0	1	1	1	1
F3+F4≥80	156	130	132	133	138	154	151	95	145	177	134	167	166	175	163	160	170	159	169	166	140	167	157
0.2≤F4/(F3+F4) ≤0.8	0.48	0.61	0.65	0.8	0.59	0.73	0.43	0.95	0.97	0.49	0.91	0.93	0.69	0.37	0.45	0.46	0.27	0.37	0.09	0.42	0.74	0.98	0.83

Figure 3.22: Correlation of FWRB (1) metric with geometrical assessment of vehicle's structures showing good agreement for all vehicles apart from those circled in red. Note: For vehicles marked with an asterisk, the vehicle's structural height was adjusted to compensate for the fact that the LCW ground clearance was not 80 mm in the test.

Whether or not a second stage for the metric is required is still under debate. Ideally all vehicles would align their PEAS or other forward structure with the common interaction zone and hence meet the Stage 1 requirements and consequently there would be no need for a second stage. Unfortunately, in the real world there are some vehicles which cannot align their forward structure with the common interaction zone because of other requirements, for example a high approach angle requirement for off-road vehicles (Figure 3.23). To assess the compatibility of these types of vehicles a second stage is needed. However, because these vehicles form a relatively small proportion of the vehicle fleet, an alternative possibility is that they could be made exempt from this requirement.

An additional part of the debate is centred on the question if not having a second stage for the metric would be design restrictive. Examples of the case in question are cross-over vehicles. These vehicles are often raised versions of their car counterparts. The result of this is that the PEAS (main rails) are no longer in alignment with the common interaction zone. To compensate for this most manufacturers have added SEAS below the PEAS to help ensure good structural interaction. However, often this SEAS is positioned rearwards of the front of the PEAS and consequently this type of vehicle would not meet the requirements of the metric with a single stage. In theory this type of design will give poorer structural interaction than a design with a forward structure in alignment with the common interaction zone because the more rearward structure will interact later in the impact. However, if the difference is small then one could argue that it should be permitted and a second stage is required. If the difference is large one could argue the opposite. Work is planned in FIMCAR Work Package 6 to investigate this issue with car-to-car crash tests and simulations in order to quantify the likely difference.

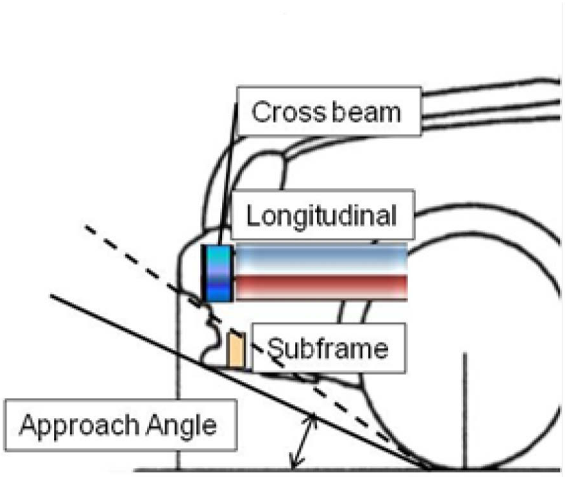


Figure 3.23: Approach angle – dotted line shows that for a high approach angle a high position of the longitudinal is required with subframe structure placed rearwards.

The options for a second stage are (1) Over-Ride Barrier (ORB) test, (2) FWRB assessment at a later time and (3) assessment using the PDB test. Some work has been performed to investigate these options.

(1) For the ORB test a number of issues have been raised. The first of these is described in Section 3.1.2.4. In summary, the test does not detect SEAS crossbeam structures adequately. A deformable element in front of the ORB may be necessary to address this issue. The second issue is that the GRSP IG FI has indicated that an additional supplementary test is not desirable because they wish to keep the number of tests to a minimum.

(2) The FWRB assessment at a later time has been investigated but a number of issues have been raised which question its feasibility. The first of these is that at a later time in the impact there is the possibility that engine dump loading could confuse the assessment. However, there is the possibility that this could be overcome by ensuring that the assessment is made before engine dump occurs by using an accelerometer mounted on the engine to detect when this occurs. The second issue is the detection of blocker beam type SEAS which are attached to the PEAS only. This type of SEAS may not be detected consistently because deformation of the PEAS behind where the blocker beam is connected can result in the blocker beam moving rearwards and not contacting the wall to load it.

(3) Initial studies have been performed to investigate the possibility of using a PDB test as a second stage to assess SEAS. The results of this work have indicated that this approach could be feasible but much further work would be required to develop an assessment.

In summary, all of the options for a second stage have significant issues. If it is decided that a second stage is needed much further work would be required to resolve them assuming that it is possible.

<u>FWRB Metric (2)</u>

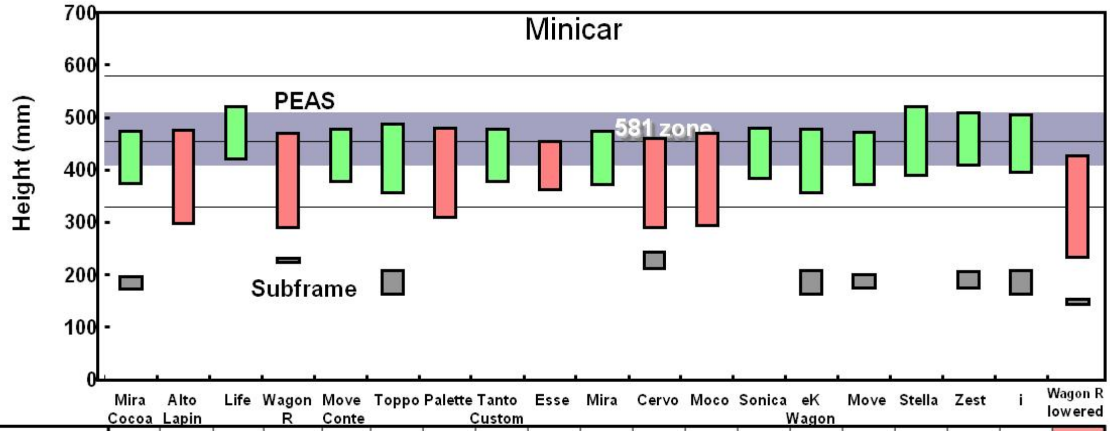
This metric is a development of FWRB (1) to ensure that vehicles that have forward located structures (i.e. forward lower load paths) positioned below the common interaction zone are not discouraged and if possible encouraged. The concept of this metric is that vehicles with forward lower load paths are encouraged by lowering the Row 3 load requirement (bottom half of common interaction zone) if sufficient load is applied to Rows 1 and 2.

The LCW 1st (F1), 2nd (F2), 3rd (F3) and 4th (F4) row forces maximums are measured at the time when the total LCW force is 200 kN and the following performance limits are applied:

F4+F3 ≥ (100 kN – LR)
F4 ≥ 35 kN
F3 ≥ (35 kN – LR)
Limit Reduction (LR) = Min [(F2+F1-25 kN); 35 kN]
Note: If (F2+F1-25 kN) is less than 0 then its value is 0

This metric ensures that the vehicle still has some 'high' structure in alignment with the top half of the common interaction zone to help prevent it being overridden, but also ensures it has some 'lower' structure in alignment with Rows 1 and 2 (instead of Row 3 as for FWRB (1)) to help prevent it overriding other vehicles.

Verification of this metric for Japanese minicars is shown below (Figure 3.24). It should be noted that the correlation of this metric assessment with the geometric assessment is improved compared to FWRB (1) metric, in particular for the Alto Lapin, Suzuki Cervo and Nissan Moco vehicles. This is because this metric has a load requirement of 35 kN in Row 4 which these vehicles fail to meet because their rails do not overlap Row 4 sufficiently. It should be noted that there is still an issue of the lack of correlation for the Tanto Custom for this metric as well as for FWRB metric (1). The explanation to why this occurs is not clear. However, it may be a result of the high loading on Row 3 possibly caused by some component attached to the engine loading the wall (Figure 3.25). This issue needs to be resolved if either of these metrics are chosen as the final proposal.



	Mira Cocoa	Alto Lapin	Life	Wagon R	Move Conte	Toppo	Palette	Tanto Custom	Esse	Mira	Cervo	Moco	Sonica	eK Wagon	Move	Stella	Zest	i	Wagon R lowered
Option 1a (%) a/b (≥50)	66.5	68.5	85.3	55.9	70.5	79.3	72.4	70.5	55.9	65.6	52.8	61.7	71.5	69.5	64.6	100	97.5	97.1	11.8
Option 1b (%) a/c (≥50)	67.6	39.1	87.0	33.5	71.6	62.0	43.3	71.6	60.0	66.6	31.5	36.0	76.4	58.8	65.6	78.2	99.0	89.6	7.1
F3+F4 (≥100-LR)	173.7	80.5	145.4	100.2	164.1	149.8	76.5	162.1	168.5	16.10	85.8	83.3	153.3	150.6	156.9	133.2	133.5	182.6	75.3
F4/(F3+F4) (0.2-0.8)	0.223	0.347	0.715	0.378	0.288	0.277	0.389	0.183	0.399	0.312	0.328	0.267	0.601	0.290	0.233	0.467	0.519	0.505	0.077
F4 (≥35)	38.8	27.9	104.0	37.8	47.2	41.5	29.8	29.7	67.2	50.2	28.1	22.2	92.1	43.6	36.6	62.2	69.3	92.3	5.8
F3 (≥35-LR)	134.9	52.6	41.4	62.3	116.8	108.3	46.7	132.4	101.4	110.8	57.6	61.1	61.1	107.0	120.3	71.0	64.2	90.3	69.5
F2	11	85.8	27.6	77.4	5	15.2	86.5	9.5	14.7	8.3	89.2	88.6	9.1	17.6	9.9	29.8	33.9	5	89.2
F1	5.3	3.2	3.6	3.6	8.8	0.8	3.5	9.7	1.5	12.8	3.1	3.6	4.2	0	10.7	3.6	10.8	0	26.2
Limit Reduction (LR)	0	35	6.2	35	0	0	35	0	0	0	35	35	0	0	0	8.4	19.7	0	35
Correlation FWRB (1) metric	1	0	1	0	1	1	1	0 ?	1	1	0	0	1	1	1	1	1	1	1
Correlation FWRB (2) metric	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1

Figure 3.24: Correlation of FWRB (1) and FWRB (2) metrics with geometrical assessment of vehicle's structures for Japanese mini-cars showing better agreement for FWRB (2) metric.

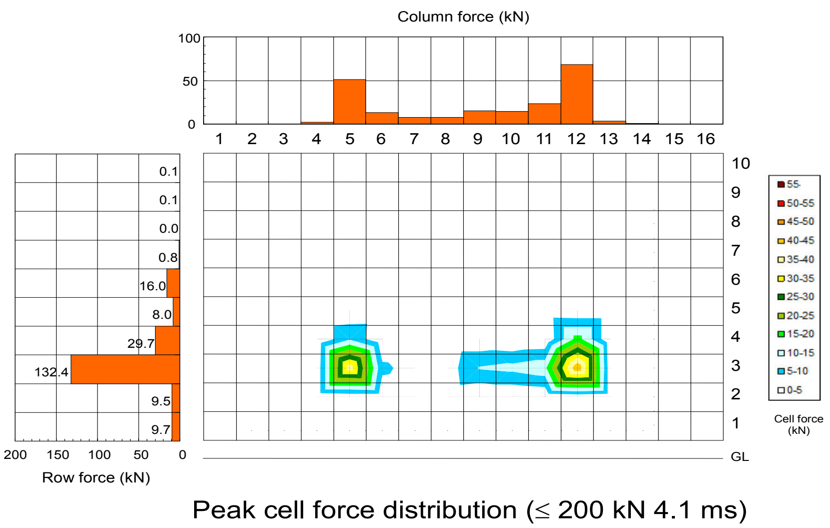


Figure 3.25: LCW peak cell force distribution at 200 kN for Tanto Custom Japanese minicar.

The position of a possible second stage for this metric is the same as for FWRB (1) metric.

<u>FWRB Metric (3)</u>

For both the FWRB (1) and FWRB (2) metrics the load distribution on the wall is assessed at the time when the total LCW force is 200 kN. As mentioned above, the main reason for this was to ensure that the assessment was made before significant engine dump loading occurred. However, for certain vehicles, in particular Japanese mini-cars which do not have crush cans, engine dump loading can occur before the LCW total force is 200 kN. For the Daihatsu Esse minicar engine dump loading on Row 4 at a LCW total force of 200 kN can be seen (red circle in Figure 3.26). Engine loading of this magnitude may not be seen in a car-to-car impact and hence may lead to an incorrect assessment of the vehicle's structural interaction potential.

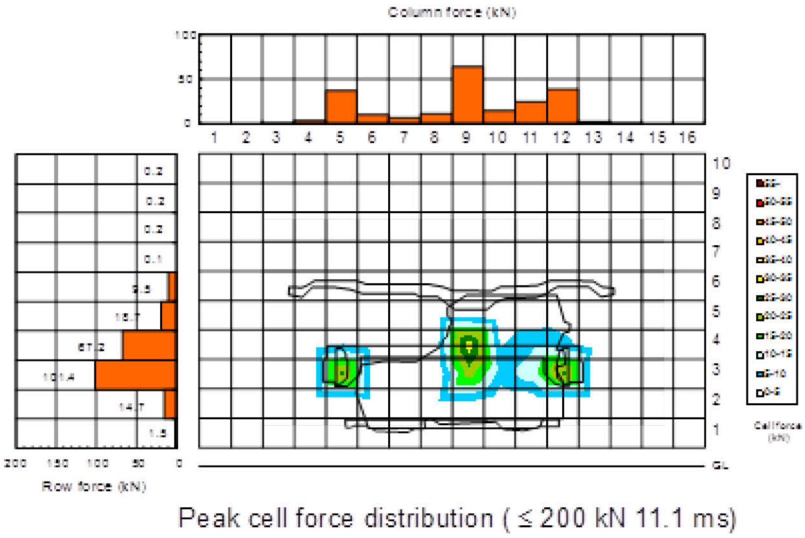


Figure 3.26: LCW peak cell force distribution at 200 kN for Daihatsu Esse minicar.

To resolve this problem FWRB metric (3) was developed based on the concept of making the assessment earlier in the impact if engine dump loading is present and applying performance limits based on the total LCW force at that time.

FWRB metric (3) is calculated as follows:

- Measure the engine deceleration when the LCW force equals 200 kN
  - If the engine deceleration < 500 m/s^2
    - Determine max F3 and F4 when total LCW = 200 kN
    - Apply following performance limits
      - F3 ≥ 35 kN
      - F4 ≥ 35 kN
      - F3 + F4 ≥ 100 kN
  - If engine deceleration > 500 m/s^2
    - Determine time when engine deceleration = 500 m/s^2 (t_{ENG500}).
    - Determine total LCW force at time t_{ENG500} ($F_{T\ ENG500}$)
    - Determine F3 and F4 at time t_{ENG500} ($F3_{ENG500}$; $F4_{ENG500}$)
    - Apply following performance limits:
      - $F3_{ENG500} \geq (35/200)\ F_{T\ ENG500}$ kN
      - $F4_{ENG500} \geq (35/200)\ F_{T\ ENG500}$ kN
      - $F4_{ENG500} + F3_{ENG500} \geq (100/200)\ F_{T\ ENG500}$ kN

Notes:

1. 500 m/s^2 was chosen for the engine deceleration because this is approximately the max deceleration of car's compartment in a full width test.

For the Daihatsu Esse the FWRB metric (3) assessment is made at 9.6 ms into the impact instead of at 11.1 ms had no engine dump loading been present (Figure 3.27). The required row load performance limits were met easily (Figure 3.28).

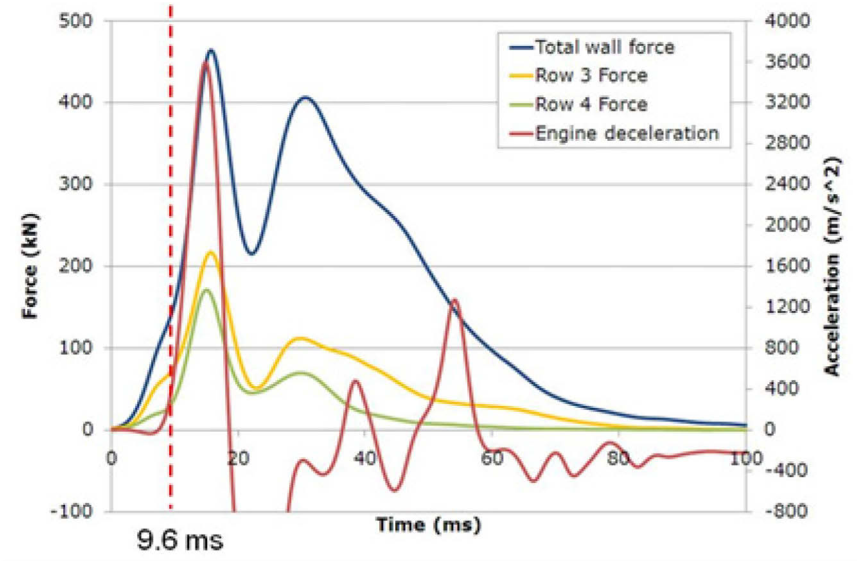


Figure 3.27: LCW total and row forces and engine deceleration for Daihatsu Esse.

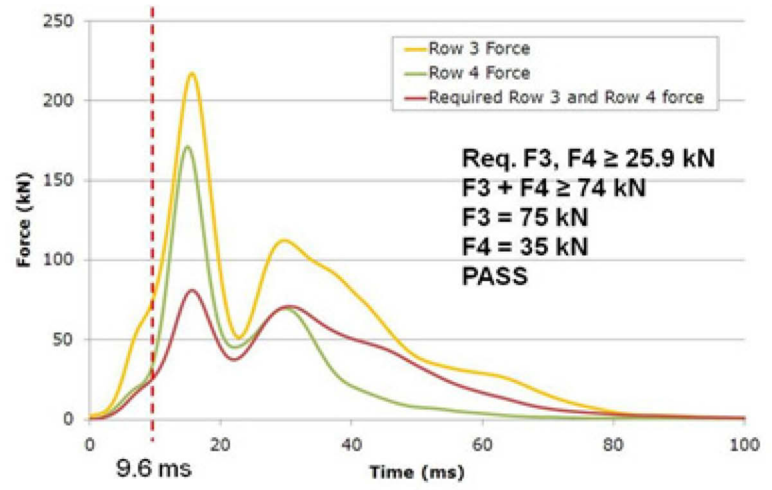


Figure 3.28: FWRB metric (3) assessment of Daihatsu Esse car earlier in impact (9.6 ms) showing that proposed performance requirements are met.

It should be noted that using FWRB metric (3) does not change the correlation of the metric assessment with the geometric assessment. This is because there were no cars in the data set for which engine dump loading affected the result of the metric assessment. However, it is theoretically possible that engine dump loading could affect the result of the assessment, for example a car could be designed with no structure in alignment with Row 4 and the engine positioned such that it loaded Row 4 to meet the Row 4 load requirement before the LCW total force reached 200 kN. This car could meet the requirements of the FWRB (1) and FWRB (2) metrics but would fail to meet an assessment earlier in the impact, i.e. the FWRB (3) metric requirements.

This metric still could be incorporated into FWRB metric (2) if it is decided that it is needed, i.e. if it is decided that the issue of engine dump loading with Japanese mini-cars is a significant problem which manufacturers may exploit to cheat the test.

Discussion and Conclusions

Three metrics have been developed for the FWRB test. The first two of these are based on an assessment of the force distribution on the LCW when the LCW total force is 200 kN. This is to ensure that the assessment is made before engine dump loading occurs and is hence not incorrectly influenced by it. The 3rd metric is a possible upgrade to the 2nd metric to ensure the correct assessment of a limited number of cars (some Japanese minicars) for which engine dump loading occurs before the LCW total force is 200 kN. For the test data available these metrics show reasonable correlation with a geometric assessment of the vehicles based on the principles of the US voluntary commitment to improve the compatibility of LTVs.

It is believed that FWRB metric (2) is a better way forward than FWRB metric (1). This is because FWRB metric (2) contains a mechanism to not discourage and possibly encourage vehicles to have load paths below the common interaction zone, whereas FWRB metric (1) does not. These load paths have been shown to help a vehicle's structural interaction potential. If it is decided that the issue of engine dump loading with Japanese mini-cars is a significant problem, it is recommended that the FWRB metric (2) should be upgraded to incorporate FWRB metric (3) to overcome this problem.

For all the metrics developed it is still uncertain whether or not a second stage for the assessment of vehicles that do not have their most forward structures in alignment with the common interaction zone is necessary. Because development of a second stage is a substantial task limited work has been performed on its development to date. This can be done when it is certain it will be needed. At present work is planned in FIMCAR Work Package 6 to try and clarify whether or not a second stage is needed.

It should be noted that some FIMCAR partners have expressed concern about the metrics that have been developed, in particular the meaningfulness of an assessment so early in the impact, i.e. at 200 kN LCW total force. For some vehicles this point occurs before the vehicle's crush cans have crushed completely and their main crash structures start to deform. Hence, the concern is that the metrics developed do not assess the performance of the vehicle's relevant crash structures directly and therefore could incorrectly assess the vehicle's structural interaction potential. This is a valid concern. One can envisage a problem for vehicles which have a forward structure (i.e. crush cans) which is at a different height to its main crash structures. However, most vehicles have their forward structure in alignment with their main crush structures so its height is representative of the main crash structures. Even so for many vehicles the cross-sectional height of the crush cans is not as large as the cross-sectional height of the main crash structure (longitudinals or PEAS). Ideally, the assessment should be made later in the impact but if this is done problems with engine dump loading occur. Hence, the current metrics for the FWRB represent the best compromise. However, if structures need to be evaluated later in the impact then the FWDB test metrics is probably the best way forward because the deformable element was developed to attenuate engine dump loads and hence enables an assessment even when engine loading is present.

3.3.3 Frontal Force Matching

In the description of compatibility characteristics, the FIMCAR consortium has listed "**Front End Force / Deformation"** as an area of compatibility that should be addressed. Within this area the concepts have been broken into two main subgroups as shown in Table 3.

Table 3: Compatibility Issues for Frontal Forces.

Front End Force / Deformation	
Deformation forces of frontal structures	**Energy Absorption Management**
Describes the frontal unit's deformation forces relative to the compartment strength of a partner vehicle	Vehicle frontal structure can absorb crash energy

"Deformation forces of frontal structures" is often discussed as "force" or "stiffness" matching and builds on the concept of sharing crash energy between the collision partners with a focus on car-vehicle impacts. "Energy absorption management" is related to the capacity of the structure in single vehicle crashes. *FIMCAR has determined that actions related to the deformation forces are not critical to resolve within the FIMCAR project but should be investigated.* Energy absorption is higher priority for FIMCAR but is not within the scope of this deliverable. An implicit assumption is that a crash barrier with minimal energy absorption capacity will ensure a minimum level energy absorption in the vehicle.

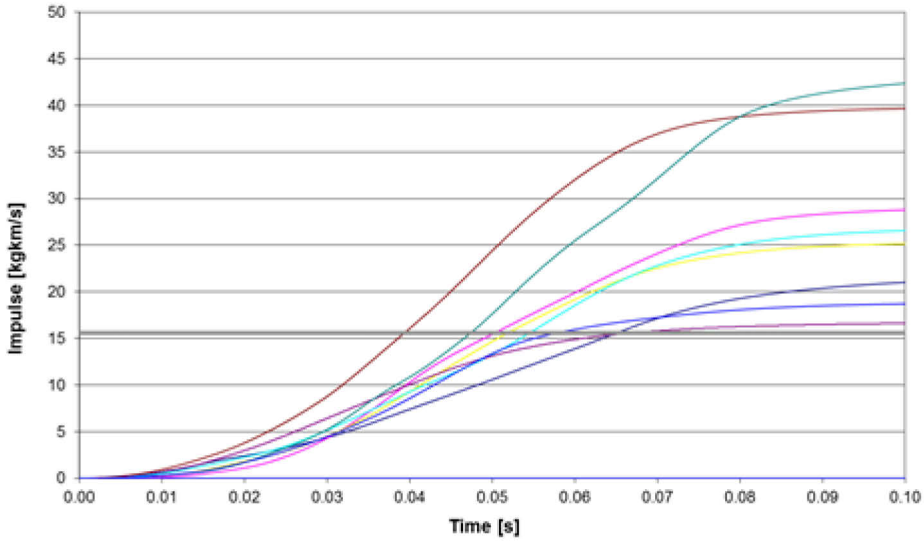
The basic physics of a collision were revisited in the development of a new performance criterion for frontal force levels. In a crash, the collision forces act over the period when the vehicles undergo a delta-v governed by their masses. Using this concept, one could specify that the force levels exchanged between the two vehicles should never exceed the compartment strength of the weakest vehicle. The concepts of impulse and momentum can be used to relate the car-to-car collision to the car-to-barrier collision. The momentum transfer between the vehicles causing the resulting delta-v can be considered equivalent to the impulse imparted on the barrier face during a crash test.

The proposed metric is based on a reference collision that causes a 1,000 kg vehicle to experience a velocity change of 56 km/h (15.6 m/s). Although the delta-v can be higher depending on the closing speed and mass ratio, the assumption is that a small car compartment can at least support the frontal forces developed in the US NCAP 56 km/h full width impact. The resulting momentum/impulse magnitude is 15.6 kgkm/s. Using the relationship that impulse is the integral of force and time, the numerical integration of the total wall forces can be used to establish the point in time when 15.6 kgkm/s is obtained. This specifies the time window in which the forces of the vehicle must be less than a specific load that will not cause compartment collapse in the partner vehicle.

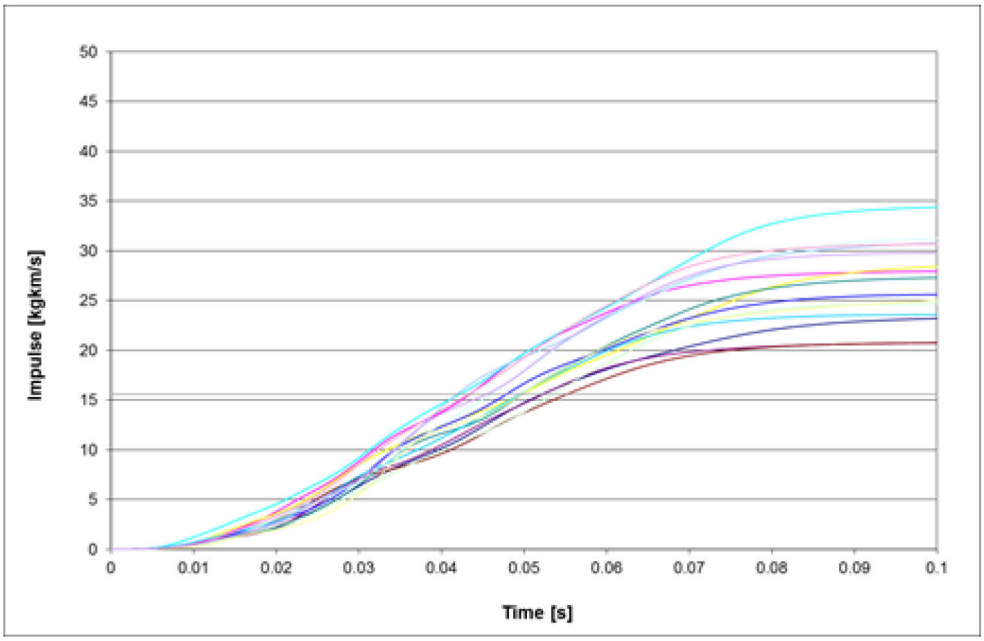
The threshold value for compartment collapse is still under discussion for offset tests although a value of 400 kN has been proposed for light cars [Faerber 2007, Edwards 2007]. Compartment collapse values for full width tests have not been truly investigated. However, since both car rails are loaded in a full width tests and tests have higher wall loads than offset tests, the 400 kN proposed for offset tests must be increased. A review of US NCAP forces suggests that a 600 kN force may be an initial threshold force for consideration. This value also represents a 60 g deceleration pulse for a 1,000 kg vehicle and is a challenge for restraint system designs in current vehicles.

3.3.3.1 Evaluation

Data from available full width deformable and rigid barrier tests were evaluated for this metric to establish the potential for this concept. As a starting point, Figure 3.29 shows the impulse/time relationship for tested vehicles with mass ranges between 900 kg and 2,500 kg. In both the rigid and deformable barrier tests it can be seen that the reference impulse level of 15.6 kgkm/s occurs between 40 and 50 ms for most cars. The deformable barrier delays the impulse curves slightly compared to the rigid barrier.



a) Deformable Barrier Data



b) Rigid Barrier Data

Figure 3.29: Impulse/Time curves in Full Width tests.

There is an issue for the criterion as the full width barrier records higher wall forces than in a real car-to-car impact due to the "engine dump" the sudden stop of the drive train in contact with an immovable wall which is not encountered in car-tp-car crashes. Since the reference impulse level occurs late in the impact, the artificially high contact loads of the drive train over-estimates the crash loads of the vehicle.

The next evaluation was to compare the contact forces of the vehicles with the impulse to identify the potential for controlling the frontal forces with the momentum based criterion. This data (for the FWDB) is shown in Figure 3.30 where the blue vertical line provides the limit of the force control (i.e., only forces left of the blue line are of interest for this metrics).

The most important information to note in Figure 3.30 is that there are three vehicles that exceed the 600 kN threshold and they exceed the 600 kN quite early in the crash. These vehicles are heavy vehicles over 1,800 kg. Figure 3.30 shows also the results of deformable barrier tests which attenuate the engine dump. Review of the rigid barrier tests showed that the engine dump effect was more pronounced and the 600 kN limit was observed for vehicles much lighter than 1.800 kg.

To understand if the forces measured in a crash against a barrier are similar to a car-to-car crash, the data from car-to-car and car-to-barrier tests were compared. The most noticeable effect was that the barrier force and the estimated contact forces for small cars were reasonably similar when a larger collision partner is involved. The FWRB is theoretically equivalent to a full frontal crash with an identical vehicle. However, the heavier vehicle experiences lower crash loads when in contact with a smaller collision partner than when in contact with a barrier. This is due to the physical limitation of the small collision partner to provide sufficient resistance to activate the heavy vehicle’s structures and generate the same contact loads as in the fixed barrier test. As a result, the heavy vehicle force in a barrier test over-predicts its reaction forces against a smaller collision partner. There is the possibility to scale the contact forces by the mass ratio of the collision partner but this may not have sufficient accuracy for regulatory application.

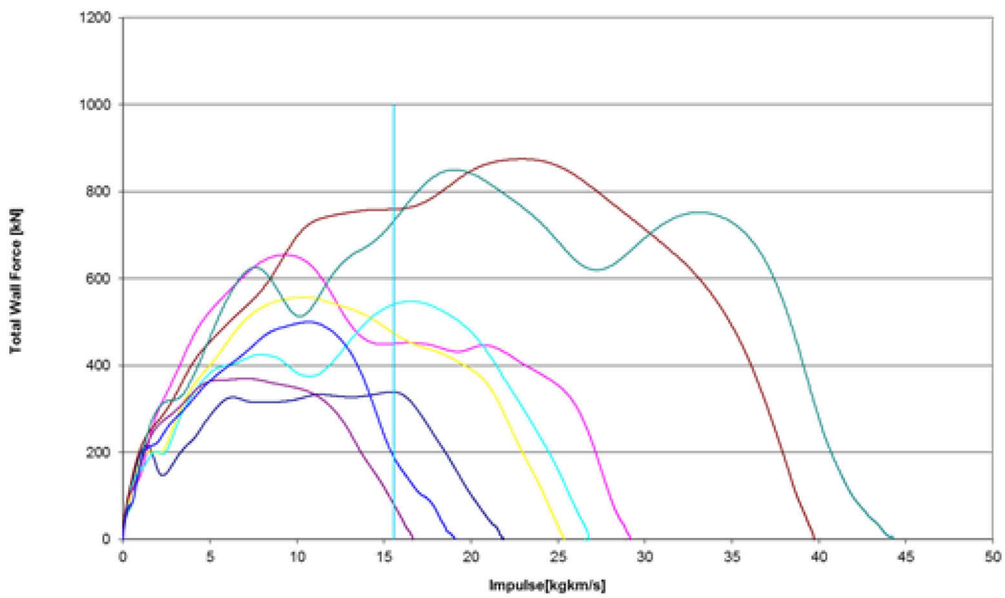


Figure 3.30: Load/Impulse curves for different vehicles.

3.3.3.2 Summary and Recommendations for FIMCAR

After reviewing the existing procedures (KW 400) and proposed impulse matching approach presented above, it is recommended not to pursue frontal force/stiffness matching criteria in FIMCAR. Deliverable D1.1 [Thompson 2013] and activities in WP6 have lowered the priority of developing this type of parameter, based on accident analyses.

The existing approaches to controlling force levels using a full width test were not suitable for the following reasons:

1) The forces in a full width test can overestimate the contact forces between vehicles due to the artificially high forces measured on a fixed barrier.
2) The crash loads measured on a barrier are not representative of a vehicle-to-vehicle collision when vehicles of different masses are involved. In particular, the heavy vehicle forces are overestimated.

4 VERFICATION OF TEST AND ASSESSMENT PROCEDURE

During the development of the metrics for the full width tests several issues arose which required further investigation. The initial issues which arose and the investigations performed using numerical modelling to resolve them are reported below. Issues which arose later and those which required test work to investigate them (such as load spreading of the deformable element and repeatability and reproducibility) will be reported in Deliverable 3.2 (Full width test protocol) / Section VIII.

In the following section, for both the FWDB and FWRB tests, the issues investigated are described together with the results and conclusions of the investigations. It should be noted that the numerical modelling work was performed by WP5 partners using the FE models that they developed for this project.

4.1 Issues

In this section an overview is given of the initial issues which have been investigated and the work undertaken to resolve them.

Table 4: List of issues and work undertaken to resolve them.

No.	Issue	Background	Method
1.	Towing hook FWRB	To investigate the effect of position on LCW force distribution and criteria. Is the load in LCW Row 3 and 4 influenced by a hard point such as the height of towing eye?	Simulation of different positions of towing eye against FWRB (Request 2)
2.	Towing hook FWDB	As above but for the FWDB	Simulation of different positions of towing eye against FWDB (Request 2 and 9)
3.	Bumper crossbeam at different height relative to longitudinals	The effect of the position of a bumper crossbeam on the LCW force distribution criteria and the performance of this car in a car-to-car test should be analysed	Analysis of previous crash test data. Also, simulation of bumper crossbeam positioned at same height as longitudinals and positioned completely below them for FWRB FWDB and car impacts (Request 1)
4.	Cross over vehicles	Investigate effect of ride height on the FWDB and FWRB assessment criteria	Simulation of cross over vehicles (Request 6)
5.	Step effects	A requirement of the FIMCAR consortium was that the metrics should not have a step effect	Simulations with the Parametric Car Models (PCM) by raising and lowering them in a stepwise manner (Request 7)

Simulations were used to address the issues listed in the Table 4 and hence verify the test and assessment procedures. As mentioned above the simulations were performed by WP5. To perform the required simulations WP3 made 'requests' to WP5. The results of the initial simulation Requests 1, 2 and 6 are described below. It should be noted that additional simulations were requested at a later date (Requests 7 and 9). The results of these simulations will be described in Deliverable 3.2 / Section VIII.

4.2 Results and Conclusions

In the following section the work undertaken is explained and analyses the issues in Table 4. The simulations are explained separately. In addition the analyses will be discussed, conclusions given, and how WP 3 decided to proceed.

4.2.1 Influence of Towing Hook on Full Width Metrics (Requests 2 and 9)

For both test procedures, FWRB and FWDB, the question came up, whether or not the loads in Row 3 and 4 of the LCW are influenced by a hard point such as the towing eye or the screw thread of this towing eye. To investigate the effect of the position on the LCW force distribution and the criteria, simulation of different positions and styles of towing eye against FWRB and FWDB have been conducted.

4.2.1.1 Protruding Towing Eye - FWRB (Request 2)

For these requests, simulations with a parametric car model PCM (category Executive) were conducted using different towing eye positions whereby the LCW force distribution and criteria were analysed. The towing eye design is simplified and consists of the towing eye itself and the towing eye support (see Figure 4.1) that is mounted on the right longitudinal with four spot-welds (see Figure 4.2).

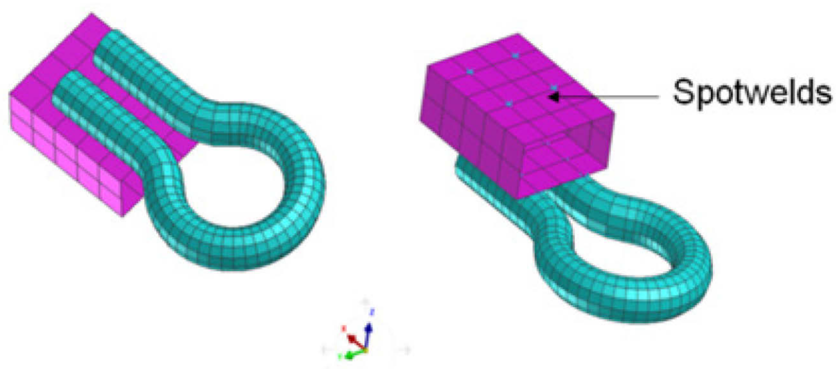


Figure 4.1: Towing eye with towing eye support.

Several assumptions (e.g., mass of towed vehicle 1,500kg, safety factor 2, material steel, only normal stress) for the design of the towing eye were made to identify the listed design parameters:

- Towing eye
    - Eye diameter = 70mm
    - Section diameter = 20mm
    - Penta elements
- Towing eye support
    - 60 x 30 x 75 mm (WxHxL)
    - t = 10 mm

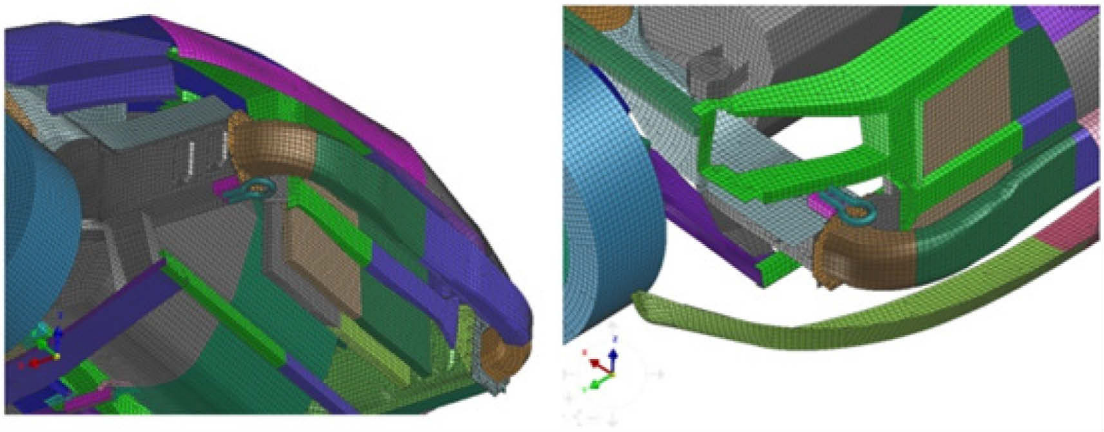


Figure 4.2: Mounting position of the towing eye on right longitudinal (left below longitudinal, right above longitudinal).

The towing eye was attached at two different positions at the right longitudinal, Figure 4.2. The impact location of the towing eye on the LCW was for the upper towing eye Row 5 and for the lower towing eye Row 3.

The simulations were conducted in general for both, the FWRB and the FWDB barrier. The unfiltered load cell wall forces of the FWRB test (basis, lower towing eye and upper towing eye) are shown in Figure 4.3. The impact of the towing eye is especially viewable in Rows 3 and 5 at around 15 ms (marked by red circles). These peaks disappear by application of the CFC60 filter which is recommended by SAE and ISO for load cell wall data.

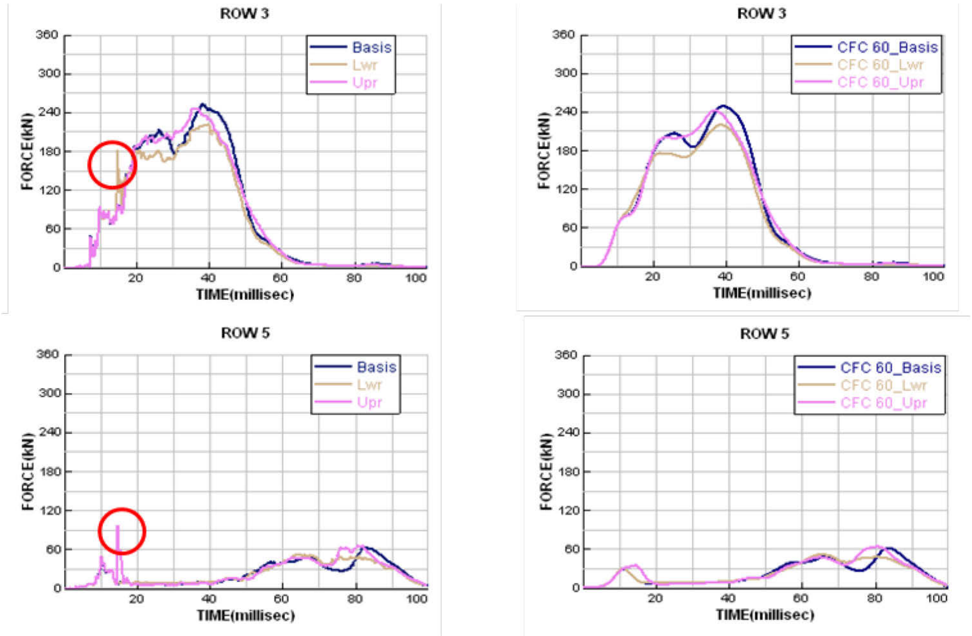


Figure 4.3: FWRB - Row 3 and 5 forces (left – unfiltered; right – filtered with CFC 60) (Impact of towing eye is marked by red circles).

The measured results of the FWRB test for Row loads 1 to 4 are summed up in Table 5. The towing eye produces no influence towards the FWRB metric functionality, when the CFC 60 filter is applied.

Table 6: Application of simulations to metrics – FWRB.

			w/o towing eye	lower towing eye	upper towing eye
FWRB (1) (Original metric)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		F3+F4 [kN]	166.7	166.9	167.2
		0.2 ≤ F4/(F3+F4) ≤ 0.8	0.62	0.63	0.62
FWRB (2) (Original metric with limit reduction)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		F3+F4 [kN]	166.7	166.9	167.2
		F3 [kN]	62.6	62.5	62.9
		F4 [kN]	104.1	104.4	104.4
		F1 [kN]	0.0	0.0	0.0
		F2 [kN]	1.5	1.4	1.4
		LR	0.0	0.0	0.0
FWRB (3) (Metric including engine dump)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.3	10.3
		$a_{eng.force=200kN}$ [g]	6.1	6.3	6.3
		$t_{engine500}$ [ms]	-	-	-
		F3+F4 [kN]	-	-	-
		F3 [kN]	-	-	-
		F4 [kN]	-	-	-

Conclusions Towing Eye FWDB and FWRB Simulations

The simulations regarding the towing eye issues on the FWRB showed that in general the towing eye influences load cell wall readings if no filtering is applied to the load cell wall data. But if the data is filtered as recommended by the ISO standards, the small peaks are smoothed. In response to this finding the application of CFC 60 filtering is recommended to avoid undesirable influences due to hard points such as a towing eye.

4.2.1.2 Protruding Towing Eye - FWDB (Request 2)

The same simulation process was undertaken for the FWDB barrier with the parametric car models. In contrast to the FWRB test results, the towing eye may produce relevant force peaks even if the CFC 60 filter (see Figure 4.4, red circles) is applied. Additionally, dependent on the location of the towing eye different results could be achieved.

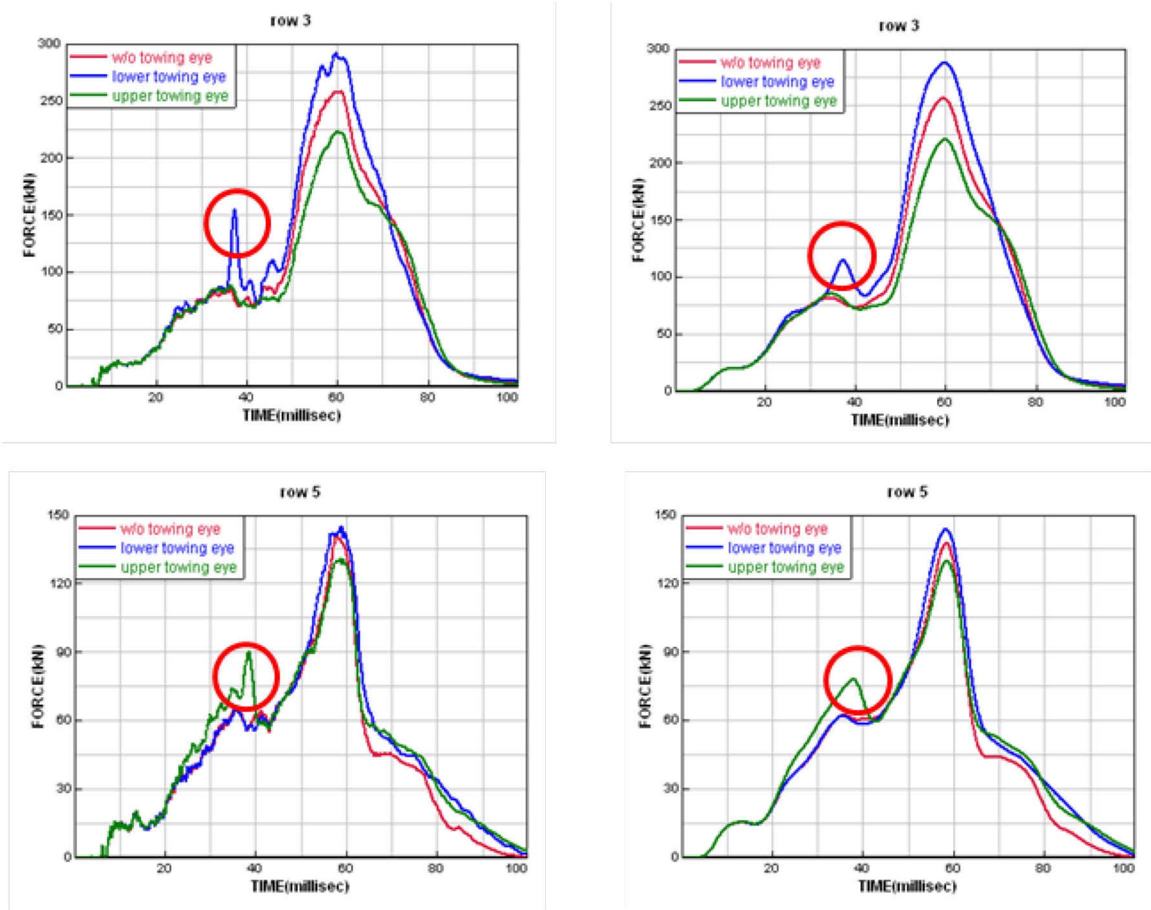


Figure 4.4: Row 3 and 5 forces (left – unfiltered; right – filtered with CFC 60) in x-direction (Impact of towing eye is marked by red circles).

Due to the deformable element in front of the rigid wall the towing eye was forced to deform in another way than in the FWRB test. This deformation applied enough forces to the wall to influence the sum forces of the corresponding row. Furthermore two different deformation behaviours could be observed (see Figure 4.5).

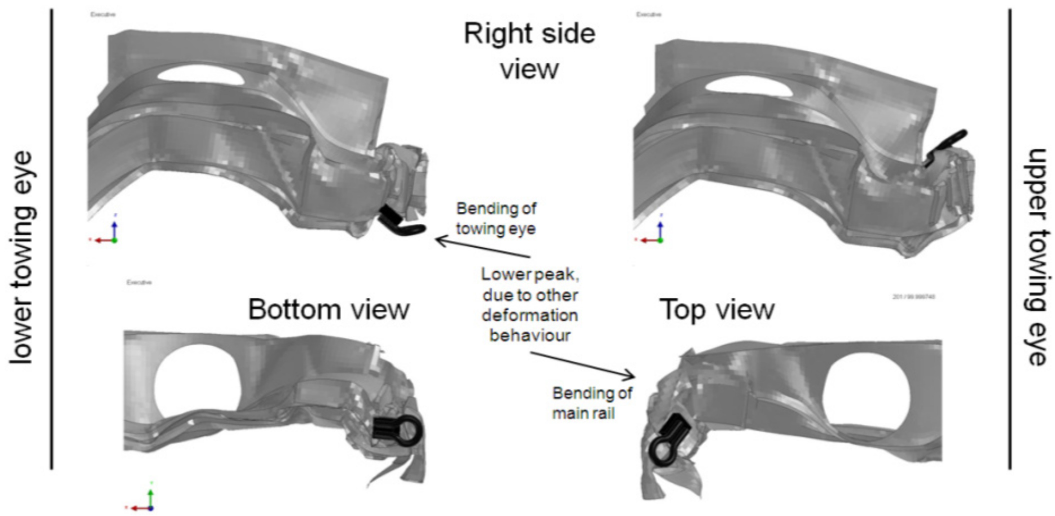


Figure 4.5: FWDB – Front structure deformations with lower and upper towing eye.

Table 7 summarises the measured load cell wall forces in the FWDB test according to Request 2 and indicates that this specific towing eye attached on the parametric car model can possibly influence the metric.

Table 7: Application of towing eye simulations to metrics – FWDB.

			w/o towing eye	**lower towing eye**	**upper towing eye**
FWDB (1)	up to LCW force 400 kN	$t_{sumforce=400kN}$ [ms]	37.3	43.0	40.9
		F3+F4 [kN]	257.33	247.0	245.7
		F3 [kN]	94.9	85.3	71.3
		F4 [kN]	163.2	161.7	174.4
FWDB (2)	up to 40 ms	F3 [kN]	89.8	94.3	72.2
		F4 [kN]	170.7	161.3	168.9
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	380.2	391.7
		0.2 * F_{t40} [kN]	78.7	76.0	78.3
		F3 [kN]	89.8	94.3	72.2
		F4 [kN]	170.7	161.3	168.9

4.2.1.3 Screw Thread - FWRB (Request 2)

Since today's vehicles are only equipped with a screw thread to attach a towing eye on the car, it seemed reasonable to model a rigid screw thread to investigate the influence in the test procedures. Following this the simulations were repeated simulating this screw thread.

The simplified (rigid) model of a screw thread was implemented at two different typical locations (see Figure 4.6).

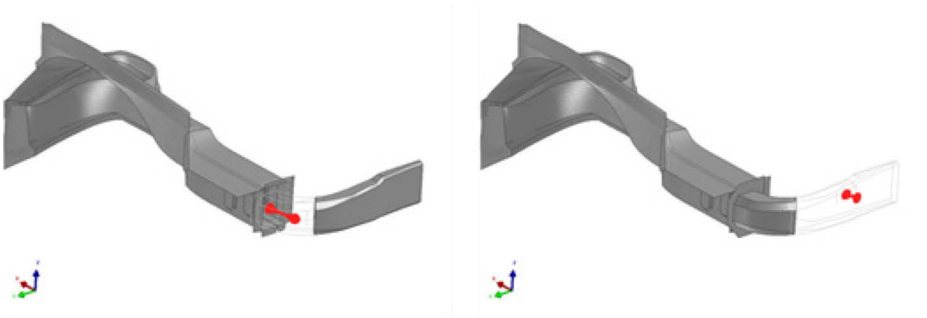


Figure 4.6: Screw thread at two different locations (left – in front of the longitudinal; right – on the right half of the cross beam).

The two models were crashed against the FWRB and FWDB. The results are comparable with those coming from the towing eye simulations. The screw thread has hardly any influence on the force distribution in the FWRB configuration, Table Table 8.

Table 8: Application of screw thread simulations to metric – FWRB.

			w/o towing eye	**longitu-dinal**	**center of right half of x-beam**
FWRB (1)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		F3+F4 [kN]	166.7	170.9	167.2
		0.2 ≤ F4/(F3+F4) ≤ 0.8	0.62	0.64	0.62
FWRB (2)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		F3+F4 [kN]	166.7	170.9	167.2
		F3 [kN]	62.6	61.9	63.3
		F4 [kN]	104.1	109.0	103.9
		F1 [kN]	0.0	0.0	0.0
		F2 [kN]	1.5	1.3	1.5
		LR	0.0	0.0	0.0
FWRB (3)	@ LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.5	10.0	10.2
		$a_{eng.\_force=200kN}$ [g]	6.1	0.1	0.1
		$t_{engine500}$ [ms]	-	-	-
		F3+F4 [kN]	-	-	-
		F3 [kN]	-	-	-
		F4 [kN]	-	-	-

4.2.1.4 Screw Thread - FWDB (Request 2)

Compared with the FWRB simulations the screw thread influences the wall force, if there is a deformable element in front of the wall, Table 9.

.

Table 9: Application of screw thread simulations to metrics – FWDB.

			w/o towing eye	longitu-dinal	center of right half of x-beam
FWDB (1)	up to LCW force 400 kN	$t_{sumforce=400kN}$[ms]	37.3	42.0	40.7
		F3+F4 [kN]	257.33	258.0	251.6
		F3 [kN]	94.9	74.4	69.9
		F4 [kN]	163.2	183.6	181.7
FWDB (2)	up to 40 ms	F3 [kN]	89.8	71.3	68.4
		F4 [kN]	170.7	177.2	178.5
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	364.9	384.6
		0.2 * F_{t40} [kN]	78.7	72.9	76.9
		F3 [kN]	89.8	71.3	68.4
		F4 [kN]	170.7	177.2	178.5

The conducted simulations showed that a local high stiffness, like a towing eye or its screw thread, works different in the two test procedures. Where it has no influence in FWRB tests, the stiff parts are responsible for other deformation behaviour of the front structures and therefore another force distribution on the wall.

To understand the deformation mechanisms observed in the FWDB simulations caused by the stiff parts the simulations were repeated with more detailed vehicle models (GCM). This was formulated in a new simulation Request 9.

4.2.1.5 Towing Hook (Screw Thread) – FWRB (Request 9)

The Generic Car Model used for this analysis was the GCM1A, i.e. the representative of Supermini class characterised by a frontal structure without the third load path. The screw thread is located inside the right crashbox and it is connected to it through a flange: this is a typical solution adopted in order to avoid/minimise the interferences between the rigid screw thread and the walls of crashbox during their folding caused by frontal impacts. GCM1A model was run against the load cell rigid wall at 56 km/h with and without the rigid screw thread (see next **Figure 4.7**).

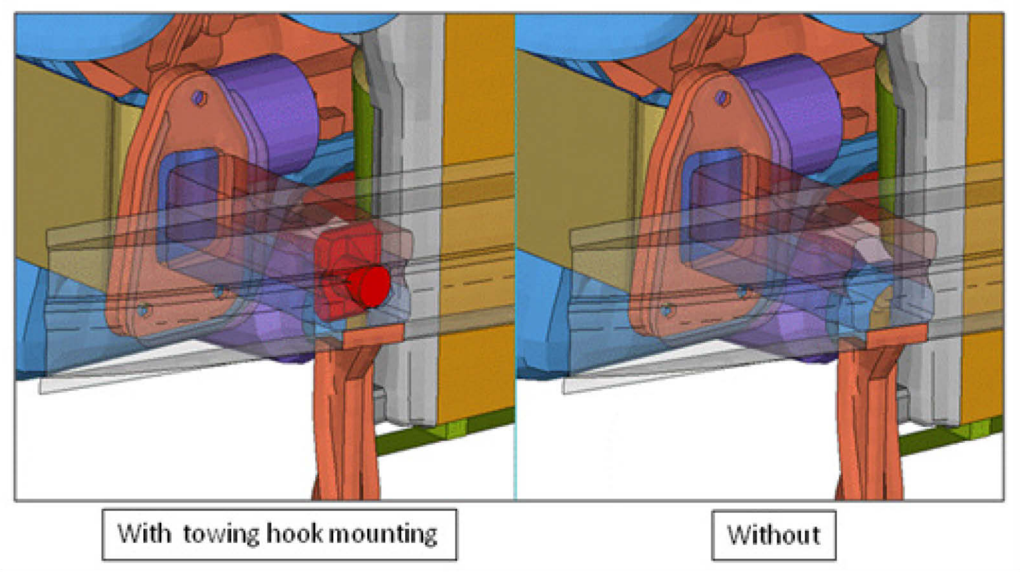


Figure 4.7: GCM1A– Right front crashbox with and without towing hook mounting.

Due to the just explained concept behind this typical solution for the towing hook mounting, no effects were detected on the load cell wall outputs as a consequence of its removal from the crashbox. In particular, the output of the load cell (named E3 in the used barrier model) directly impacted by the concerned part of the vehicle structure was examined and no differences were highlighted, for both filtered and unfiltered load cell signals. The next two figures visualise these obtained results.

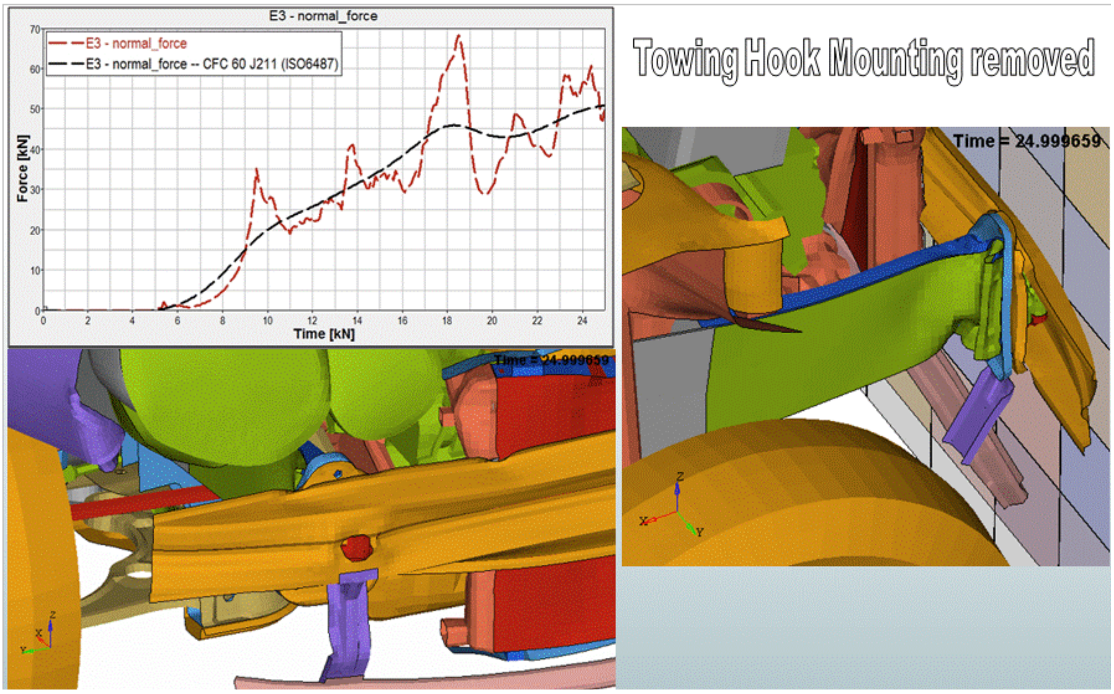


Figure 4.8: Load on directly impacted cell: run without towing hook mounting.

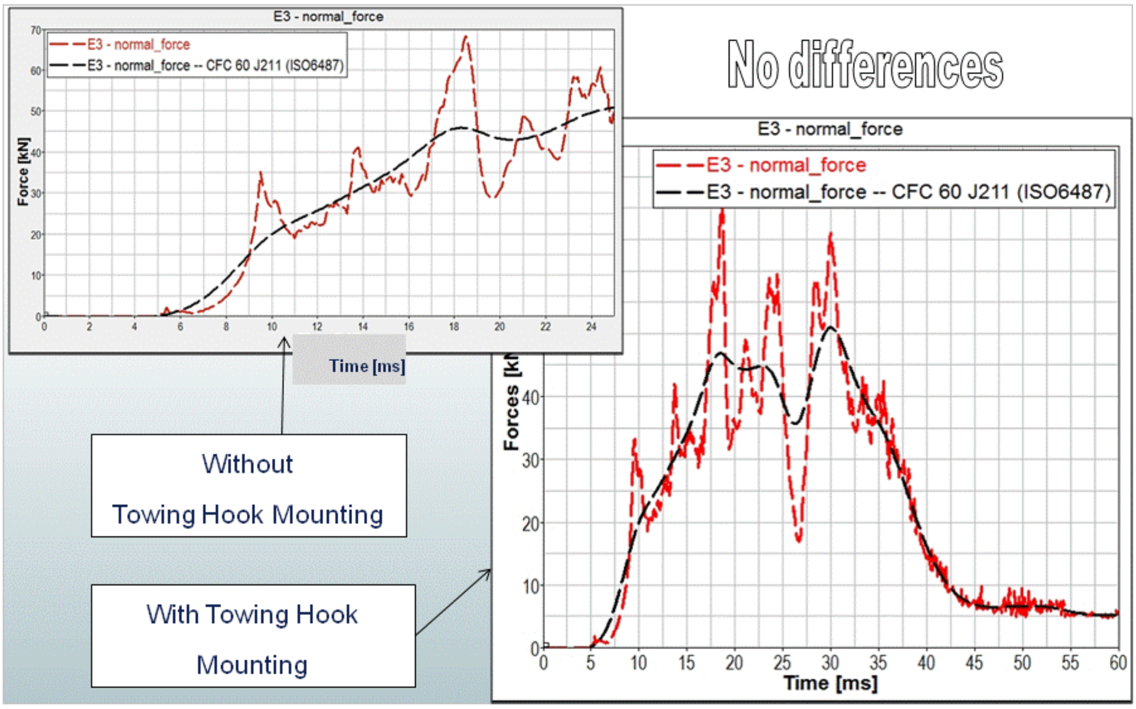


Figure 4.9: Load on directly impacted cell: comparison between runs with and without towing hook mounting.

4.2.1.6 Towing Hook (Screw Thread) – FWDB (Request 9)

The same simulation process was done for the GCM1A impact against FWDB barrier at 56 km/h. The presence of the deformable element changes the deformation mode of the crashbox, w.r.t. the collapse observed in the impact against the rigid wall: in fact the crashbox now is subjected to a downward bending, instead of collapsing axially in folding (see **Figure 4.10**, were the deformed structures, with and without towing hook mounting, are shown against the complete deformable element in the upper part and with the first layer of FWDB masked in the lower part).

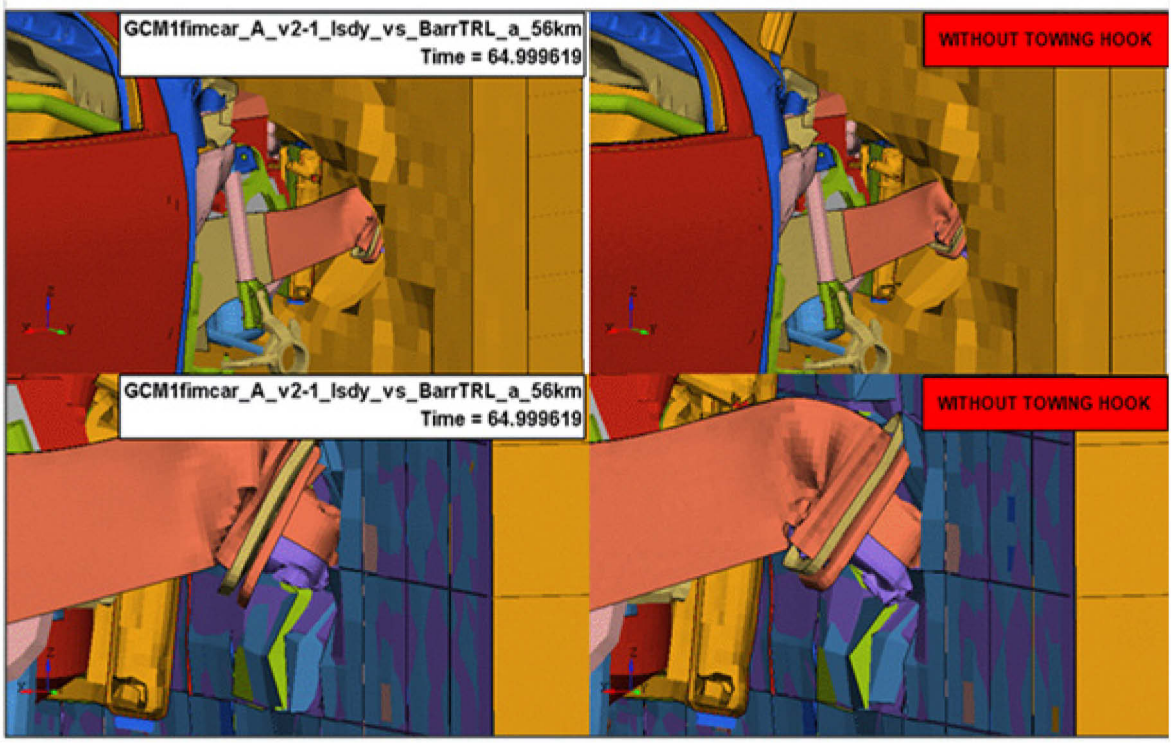


Figure 4.10: GCM1A-to-FWDB: structural deformations with and without towing hook mounting.

Some very slight differences were detected when the total barrier forces and the loads in Row 3 and Row 4 were compared for the two simulations: the analysis of the deformed shape of the crashbox and main rail highlighted only few small local differences in the way the section walls collapse. However, these differences are not affecting significantly the overall collapse mode of the structure and if the outputs from the two load cells directly behind the area covered by the concerned structure (named E3 and E4 in the model) are examined, no significant differences between load–time histories are detected, for both unfiltered and filtered signals.

The following Figure 4.11, Figure 4.12 and Figure 4.13 show the above mentioned situation.

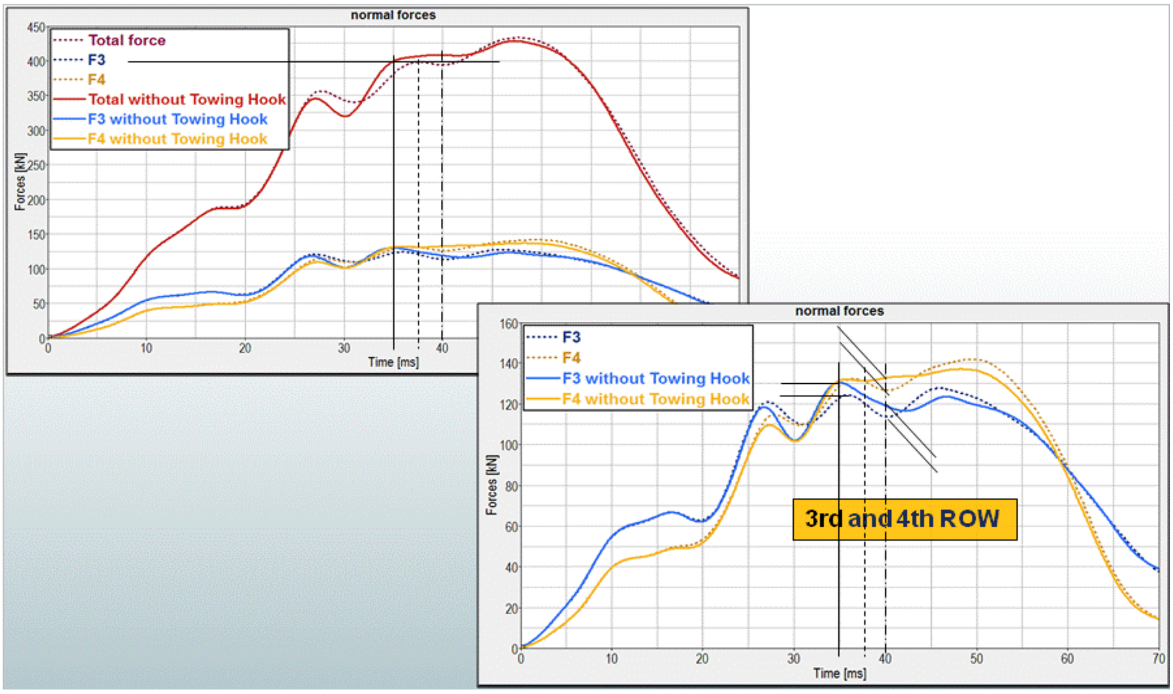


Figure 4.11: GCM1A-to-FWDB: Total, 3rd and 4th row forces vs. time plots, with and without towing hook mounting.

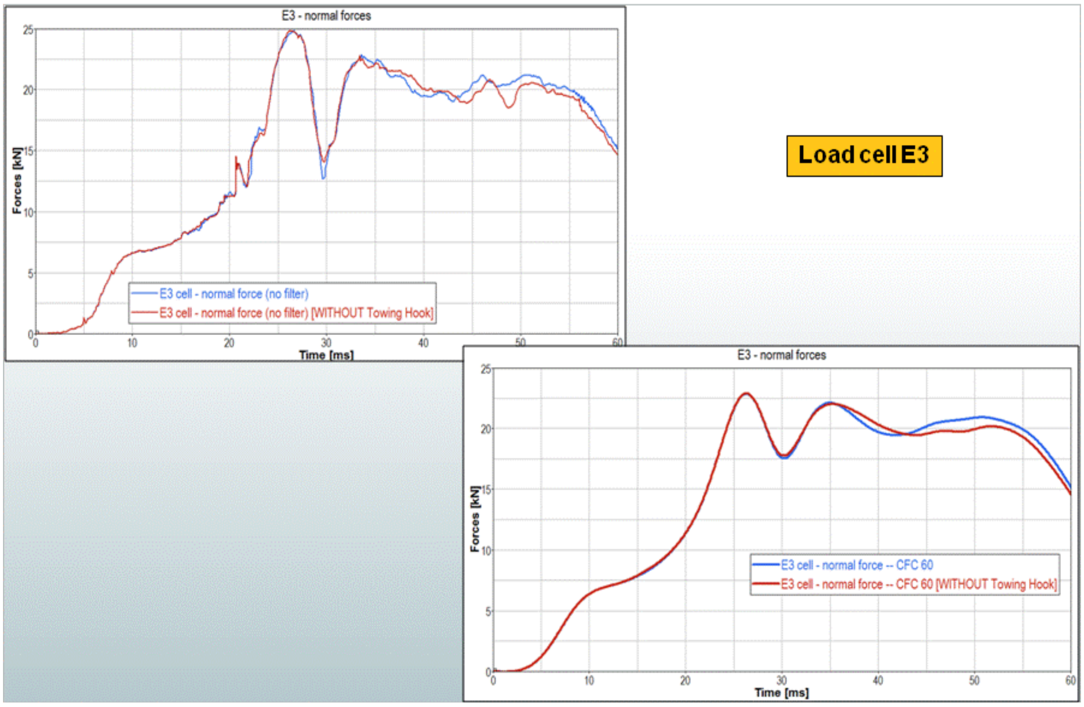


Figure 4.12: Load on (lower) directly impacted cell: comparison between runs with and without towing hook mounting.

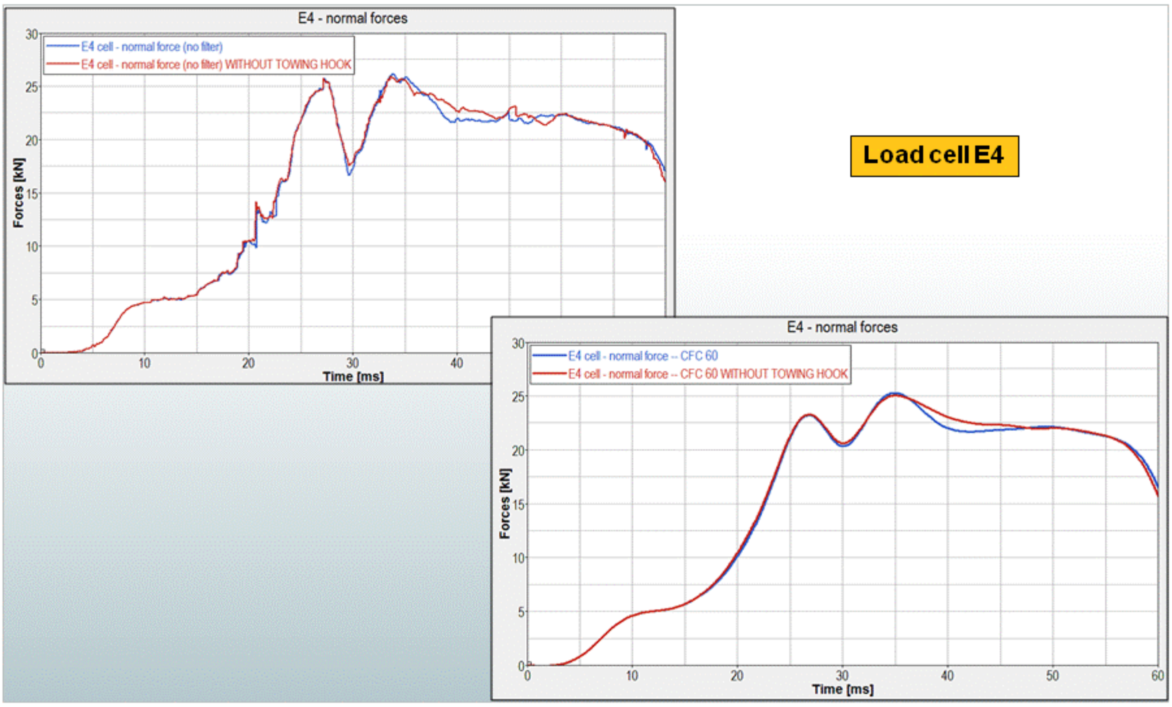


Figure 4.13: Load on (lower) directly impacted cell: comparison between runs with and without towing hook mounting.

4.2.1.7 Conclusions from Requests 2 and 9

For the FWRB differences in the LCW readings were observed using the PCM approach and protruding towing eyes before filtering. However, applying the standard filter for load cell wall data (CFC 60) the effect disappeared. In addition the influence was not observed when the standard bolt-in type was used. For FWDB the old type of towing eye could influence the metric even with a CFC 60 filter. However, the bolt-in type of towing eye used on modern vehicles showed no influence with a CFC 60 filter.

4.2.2 Variable Cross Beam Height (FWRB and FWDB) (Request 1)

For this request the parametric car model, category “Executive” was chosen as the basis model and the “Super Mini” is used exclusively for car-to-car simulations. Within the conducted simulations against the FWRB (test vehicle speed: 56 km/h) specified modifications (see Table 10) are considered in a four-step approach. The main objective of this simulation addresses the possibility to pass the metric with a cross beam which is attached in the preferred height while the location of the longitudinal is not. To investigate this objective goals are defined on the one hand to pass the metric anyway and on the other hand to compare the metric assessment and car-to-car simulations.

Table 10: Vehicle structure modifications used for Request 1.

Modification (abbreviation)	Description
mod_1	Increase the vertical position of the longitudinals and cross beam until the vehicle fails the metric
mod_2	Lowered cross beam and variations of connections and stiffness of the structures (cross beam below and within main rails)
mod_3(_1/2)	Cross beam below main rails, but in front of them, different connection stiffness
mod_4	Lowered cross beam (misalignment of structures)
mod_5	Same configuration like mod_4, but placed as far forward as possible

As first step the height of the longitudinals and the crossbeam is increased by 50 mm that implies failing of both metrics and is shown in Figure 4.14.

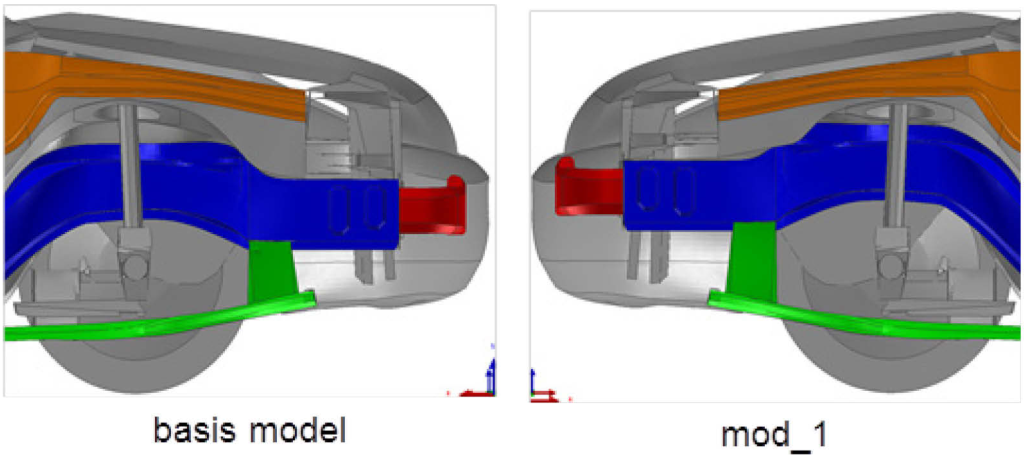


Figure 4.14: Step 1 - modification 1.

In a second step, the height of the crossbeam is decreased. For that purpose the original connection between cross beam and longitudinals was deleted and a new one was designed. Hereby, connection issues appear on the one hand due to missing information about the real connection points and on the other hand the deformation behaviour of the longitudinals is strongly influenced by the plastic buckling. Furthermore, the new crossbeam is placed in front of the longitudinals with different stiffness. The modifications 2 and 3 are shown in Figure 4.15.

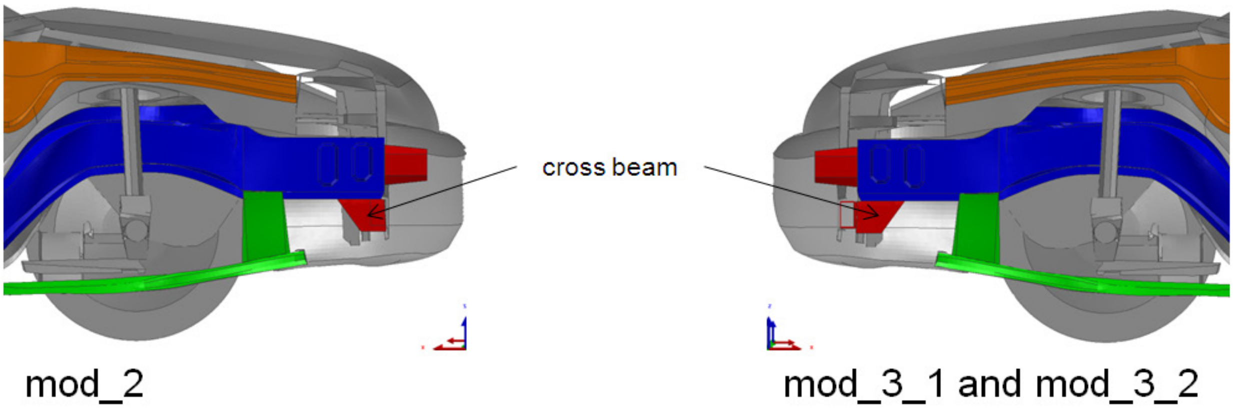


Figure 4.15: Step 2 - modifications 2 and 3.

In the third step the height of the crossbeam is decreased so that there is a geometrical mismatch between the crossbeam and the longitudinals (dotted line in Figure 4.16).

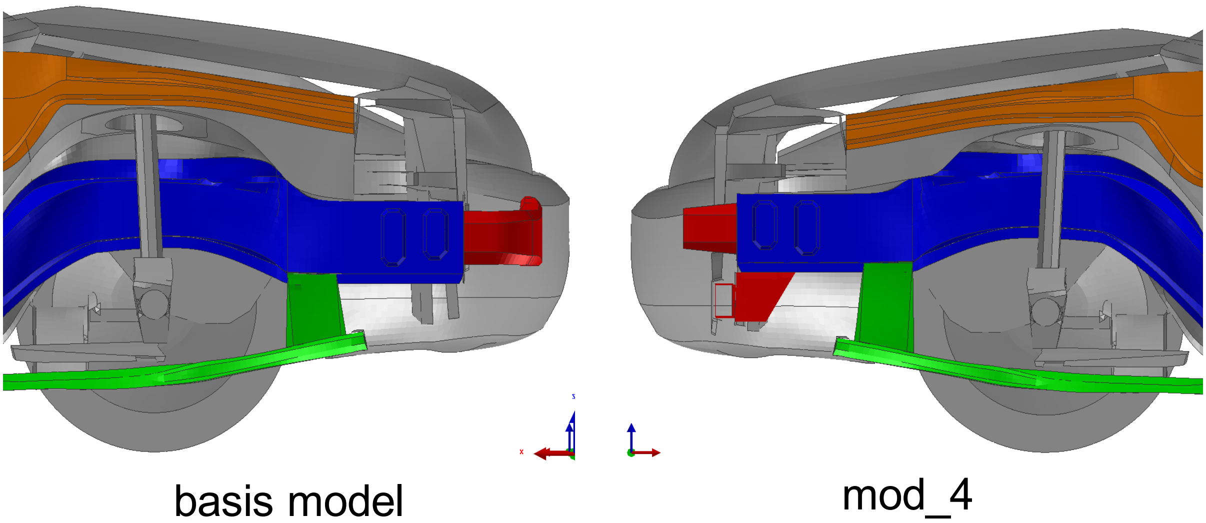


Figure 4.16: Step 3 - modification 4 against the basic model.

For the last modification the cross beam attachment of modification 4 was used. But the crossbeam was moved far as possible to the front bumper (see Figure 4.17). The intention of this was to check if the crossbeam is capable to apply enough forces to the wall to pass the metrics.

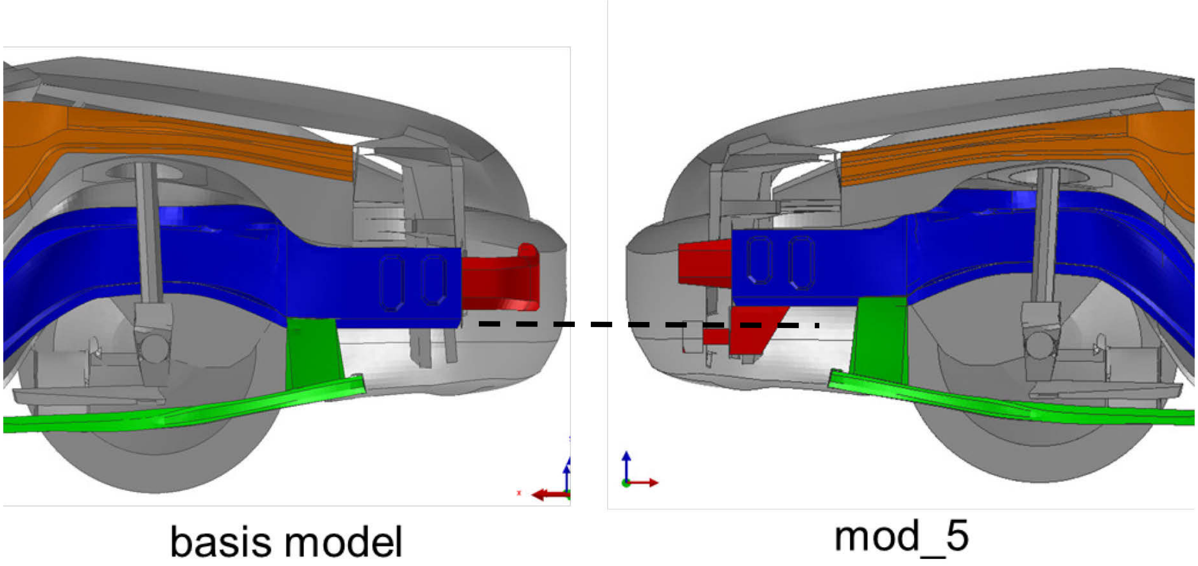
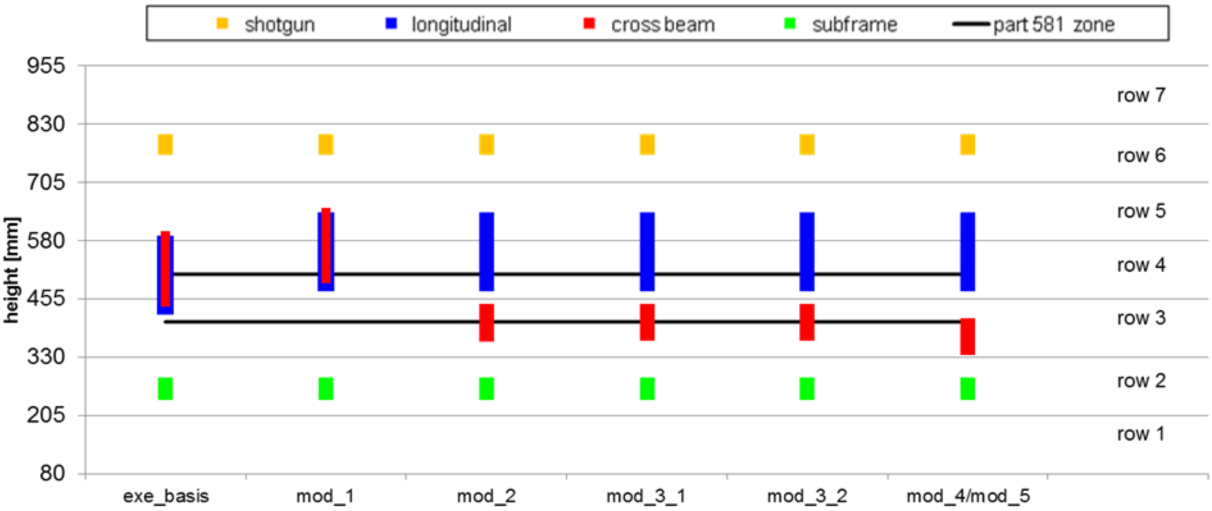


Figure 4.17: Step 4 - modification 5 against the basic model.

All modifications and hence modified heights of the energy absorption structures (EAS) are shown in Figure 4.18 together with the basic model and the part 581 zone (common interaction zone).



mod_1 = increased height of cross beam
mod_2 = cross beam below and within main rails
mod_3(_1/2) = cross beam below main rails, but in front of them, different stiffness of connection
mod_4 = lowered cross beam (misalignment of structures)
mod_5 = cross beam moved far as possible to front of vehicle

Figure 4.18: Geometric results of modifications 1 to 5.

The model with the different structure changes was tested against the FWDB and the FWRB. The final results for the different row load out of the conducted simulations for Request 1 and the metric application for the FWRB are summarised in Table 11.

Table 11: Application of simulations to metric – FWRB.

		basis	mod_1	mod_2	mod_3_1	mod_3_2	mod_4	mod_5
FWRB (1)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	F3+F4 [kN]	186.9	106.4	122.4	140.8	145.7	131.2	120.6
	$0.2 \leq F4/(F3+F4) \leq 0.8$	0.64	0.98	0.89	0.72	0.72	0.75	0.77
FWRB (2)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	F3+F4 [kN]	186.9	106.4	122.4	140.8	145.7	131.2	120.6
	F3 [kN]	67.5	2.3	13.03	40.0	40.4	32.2	28.3
	F4 [kN]	119.5	104.1	109.4	100.7	105.3	99.0	92.3
	F1 [kN]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	F2 [kN]	1.4	1.5	4.1	4.7	4.9	11.1	8.8
	LR	0.0	0.0	0.0	0.0	0.0	0.0	0.0
FWRB (3)	$t_{sumforce=200kN}$ [ms]	10.7	10.6	17.4	16.8	16.7	16.8	12.6
up to LCW force 200kN	$a_{eng.force=200kN}$ [g]	5.1	3.9	11.6	1.6	3.4	2.1	4.2

Within the analyses for the FWRB some remarkable observations were found:

- The wall force limit of 200 kN was reached later (10 ms → 17 ms) for the different modifications compared to the basis version. The engine dump occurs after ~55 ms.
- In the modification 3, an additional crossbeam was attached below and in front of the longitudinal. This modification (mod_3) was capable to apply enough forces to the LCW to fulfil the metrics of FWRB (1). However, the values were borderline.
- Modification 4 (structural mismatch with basis model) as well as modification 5 was not able to apply enough forces into Row 3 to pass the metric.

The final results out of the conducted simulations for Request 1 and the metric application for the FWDB are summarised in Table 12.

Table 12: Application of simulations to metric.

			basis	mod_1	mod_2	mod_3_1	mod_3_2	mod_4	mod_5
FWDB (1)	up to LCW force 400 kN	$t_{sum400kN}$[ms]	37.3	44.0	42.5	45.0	39.3	45.3	44.0
		F3+F4 [kN]	257.3	204.84	226.6	208.7	206.3	205.6	207.5
		F3 [kN]	94.1	36.9	61.6	56.3	70.4	50.0	55.4
		F4 [kN]	163.2	167.9	165.0	152.4	135.9	155.6	152.1
FWDB (2)	up to 40 ms	F3 [kN]	89.8	39.0	84.8	60.4	68.33	58.9	50.4
		F4 [kN]	170.7	158.0	120.6	133.3	147.9	137.4	99.1
FWDB (3)	up to 40 ms	F_{t40} [kN]	393.4	376.4	367.7	371.3	412.1	377.4	307.5
		0.2*F_{t40}[kN]	78.7	75.3	73.5	74.3	82.4	75.9	61.5
		F3 [kN]	89.8	39.0	84.8	60.4	68.33	58.9	50.4
		F4 [kN]	170.7	158.0	120.6	133.3	147.9	137.4	99.1

Within the analyses for the FWDB following remarkable observations were found:

- The wall force limit for 400 kN was reached after a later time (37 ms versus 44 ms), whereby no engine dump occurred.
- The basic model fulfils the requirements for all proposed metrics.
- The modification 2 (lowered cross beam) also fulfils the requirements of the metrics while this was not the case for the other modifications.

Comparing the results for the FWRB and FWDB differences are identified in the deformation behaviour of the PEAS. The honeycomb hardness is responsible for the bending of the lowered crossbeam (no supporting structures behind the crossbeam) and hence the applied forces on the LCW in the FWDB test are lower than in the FWRB test. The vehicle would pass the FWRB test, but would fail the FWDB test. Figure 4.19 shows the varied results of the deformed crossbeam for both barrier tests.

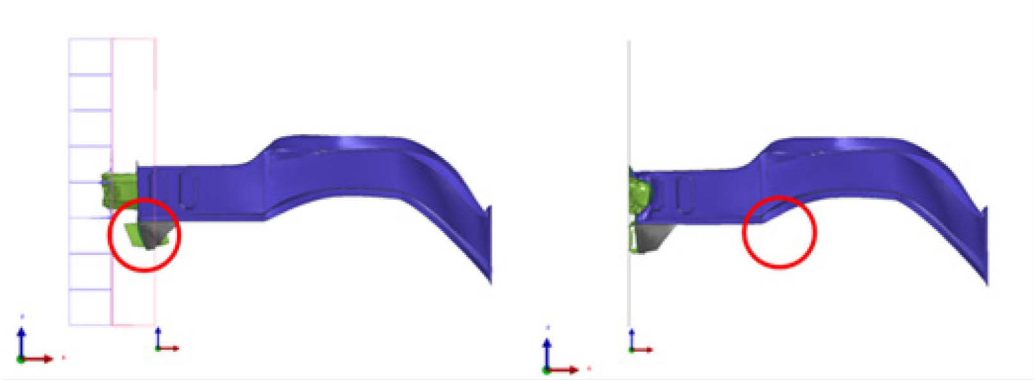


Figure 4.19: Deformation of the attached crossbeam in FWRB and FWDB test.

Conclusions Requests 1

When the test data from Japan was analysed, one vehicle was conspicuous. This vehicle has a crossbeam attached underneath the PEAS structure and this crossbeam produced forces in Row 3 and 4 although the PEAS were partially above these two rows.

In simulation Request 1, it was investigated whether or not adequate structures in Row 3 and 4 can be mocked up in FWRB and FWDB tests. The simulation results showed that depending on the specific design of the structure it is possible to influence the metric in particular with the rigid barrier. On the other side the deformable element in the FWDB test alters the deformation pattern in a way that the real load paths can be detected. Following this the FWDB is able to detect weak structures that are not supported by stiff structures behind them. In case of a collision these weak structure are not capable to offer the opposing car a possibility to interact properly.

4.2.3 Cross-Over Vehicles (Request 6)

The aim was to simulate cross-over vehicles in order to investigate the effect of differences in ride heights according to FWB assessment criteria. Simulations were conducted with the parametric car model (Large Family Car) which is tested against the FWRB and the FWDB. The cross-over version is modified by a horizontal offset of the barrier of 60 mm.

The simulation with the FWRB results in the LCW forces are shown in Figure 4.20 without the applied offset and in Figure 4.21 with the barrier offset of 60 mm.

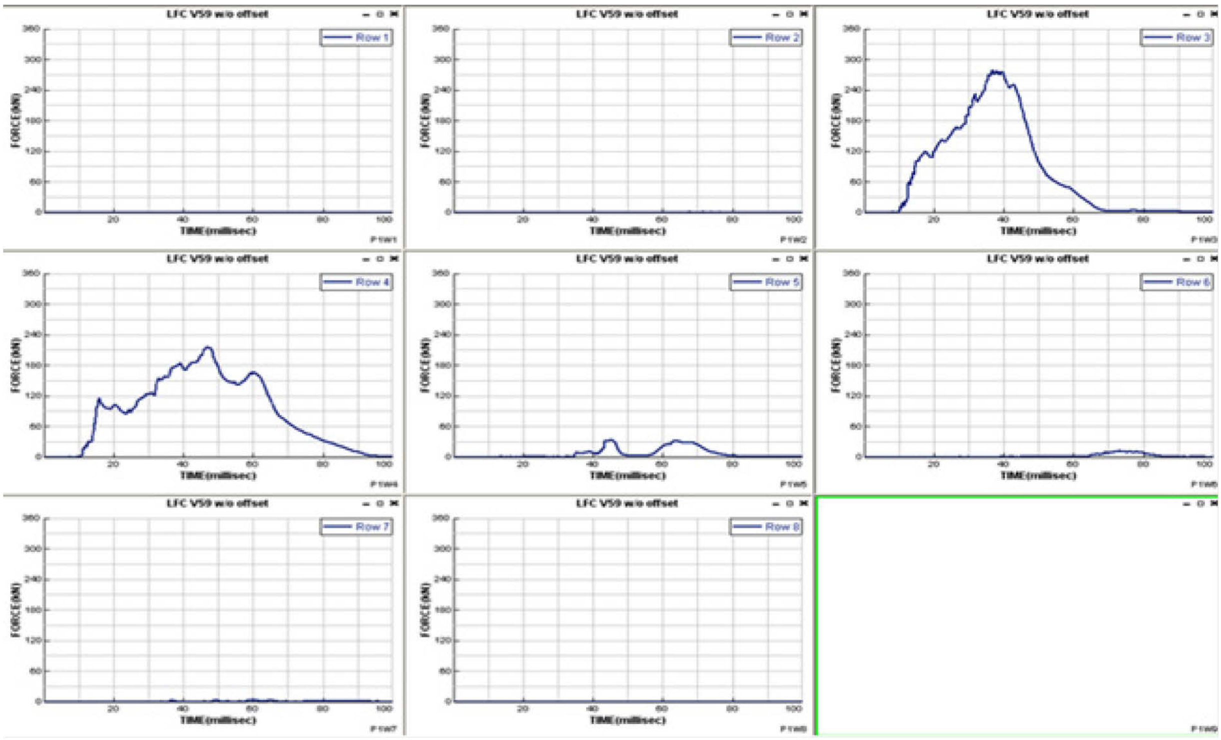


Figure 4.20: FWRB - Load cell wall forces in x-direction (without offset).

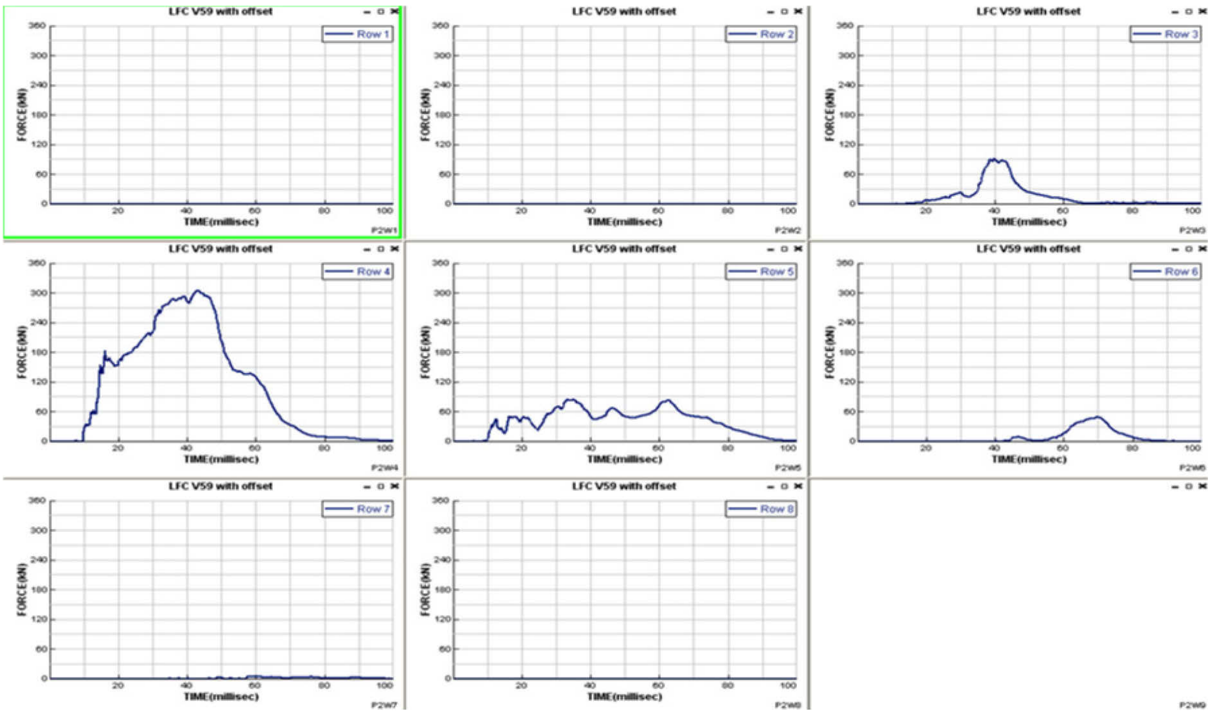


Figure 4.21: FWRB - Load cell wall forces in x-direction (with barrier offset).

Figure 4.21 summarises the measured load cell wall forces in the FWRB test with and without barrier offset according to Request 6 and indicates that the cross-over vehicle would fail the metric.

Table 13: Application of simulations to metric – FWRB

			LFC	LFC - offset
FWRB (1)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		F3+F4 [kN]	191.6	134.4
		0.2 ≤ F4/(F3+F4) ≤ 0.8	0.5	0.95
FWRB (2)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		F3+F4 [kN]	191.6	134.4
		F3 [kN]	94.9	7.1
		F4 [kN]	96.6	127.3
		F1 [kN]	4.8	0.0
		F2 [kN]	17.3	0.9
		LR	0.0	0.0
FWRB (3)	up to LCW force 200kN	$t_{sumforce=200kN}$ [ms]	10.6	10.6
		$a_{eng.force=200kN}$ [g]	13	13

Repeating these simulations per Request 6 with the FWDB leads to the LCW forces (filtered with CFC60) shown in Figure 4.22. Hereby, both tests, with and without barrier offset are included.

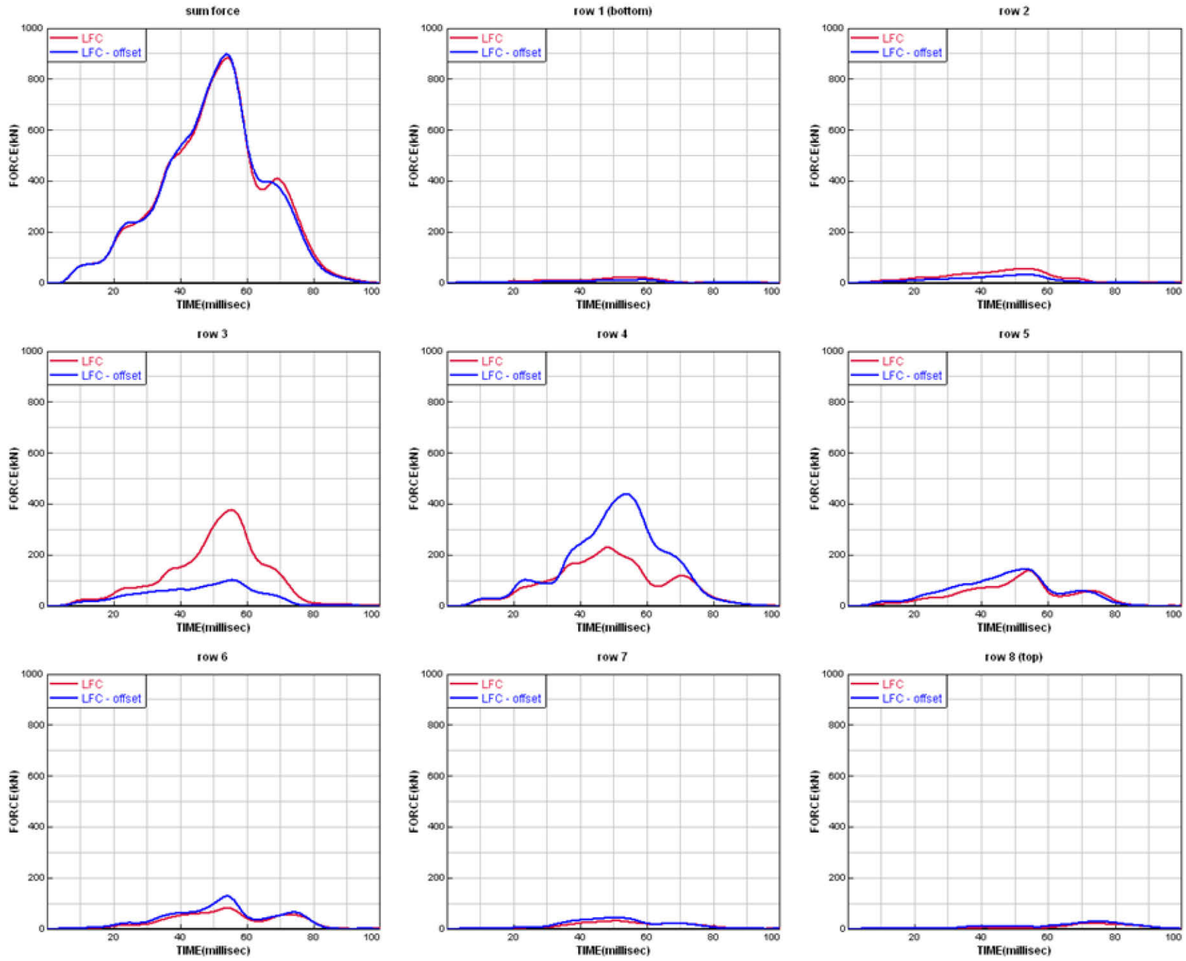


Figure 4.22: FWDB - Load cell wall forces (CFC60) in x-direction (with and without barrier offset). Table 14 summarises the measured load cell wall forces in the FWDB tests with and without barrier offset according to Request 6 and indicates that the cross-over vehicle would fail the metric.

Table 14: Application of simulations to metric – FWDB.

			LFC	LFC - offset
FWDB (1)	up to LCW force 400kN	$t_{sumforce=400kN}$ [ms]	34.7	34.9
		F3+F4 [kN]	247.2	213.7
		F3 [kN]	113.4	58.1
		F4 [kN]	133.8	155.6
FWDB (2)	up to 40 ms	F3 [kN]	149.9	63.8
		F4 [kN]	167.4	241.5
FWDB (3)	up to 40 ms	F_{t40} [kN]	511.9	532.2
		0.2 * F_{t40} [kN]	102.4	106.44
		F3 [kN]	149.9	63.8
		F4 [kN]	167.4	241.5

Conclusions Request 6

If a vehicle will be raised in order to produce a so called “cross-over” vehicle, then it can possibly fail when the structure will not be changed in a correct manner. But to raise just the vehicle means also that there will not be enough structural alignment in a car-to-car crash. For those cars it is recommended to use secondary load paths that are placed within the common interaction zone. The question if the metrics can assess these secondary structures correctly is part of current investigations.

4.2.4 Step Effects (Request 7)

In this task the simulation Request 7 will be explained which was established by WP 3 to investigate possible step effects of the metrics. A requirement of the FIMCAR consortium was that the metrics should not have significant step effects. In order to investigate this, simulations with the parametric car models were conducted by raising and lowering them stepwise to check the continuity of the FWRB and FWDB metrics. After this work the results should be verified by additional car-to-car simulations. In the end the sensitivity of the impact heights on the full width assessment criteria were investigated.

For this investigation a large family car was used to test it against the FWRB and the FWDB. The simulation of different ride heights was realised due to vertical translation of the barrier heights. Figure 4.23 shows the test configuration for the Parametric Car Model in relation to the rows of the load cell wall.

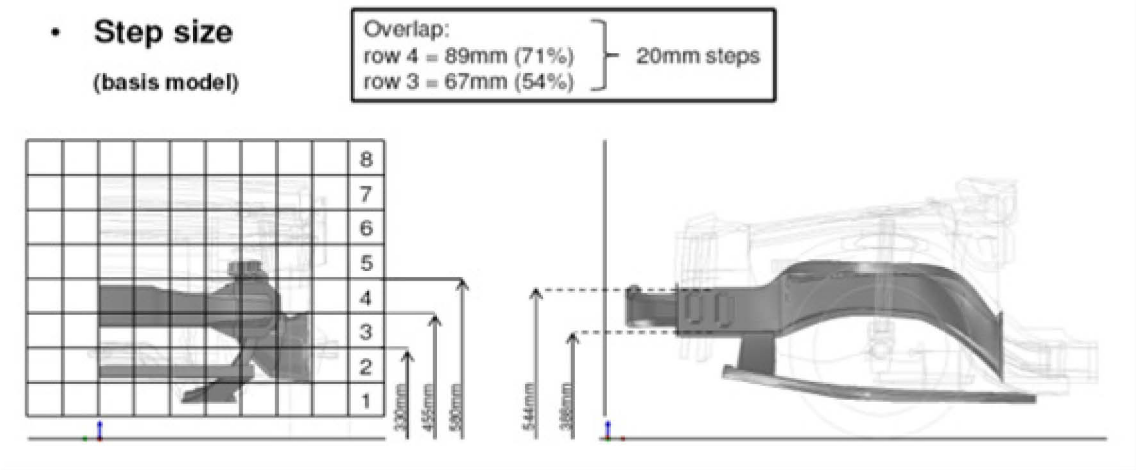


Figure 4.23: Test configuration for the investigation of step effects with PCM (large family car).

Figure 4.24 shows the results for the **FWRB**. On the left side the forces of the Row 3 and 4 are displayed by the formula F4/(F3+F4). On the right side the individual forces of Row 3 and 4 are displayed. A reasonable correlation can be observed. Also there were no strong step effects and a good correlation between overlap of the rows and the applied forces. The right picture shows that the forces in Row 4 are zero if there is no overlap with the structures in this row. But when the structures are increasing then the forces in Row 4 are also increasing and at the same time decreasing in Row 3.

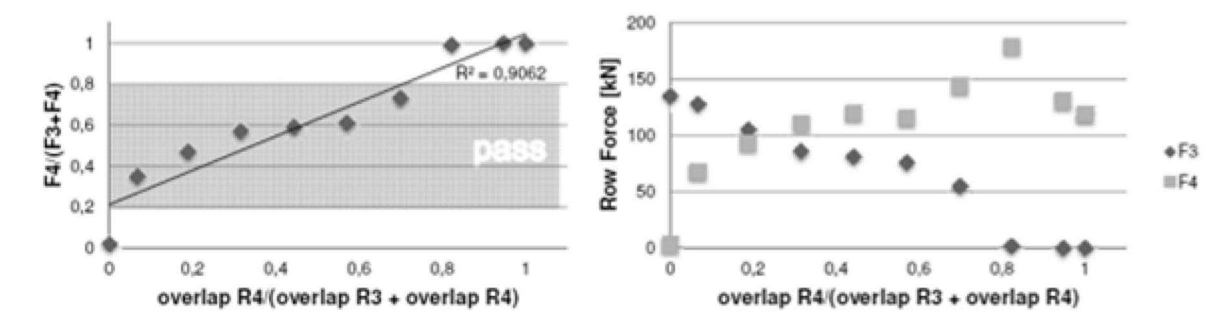


Figure 4.24: Influence of ride height on forces in Row 3 and Row 4 (FWRB), left picture shows the relation of Row 3 and 4 from the FWRB metric (1), right graph shows the individual forces of Row 3 and 4.

The results for the **FWDB** metrics are shown in Figure 4.25. The left graph shows the individual row forces up to LCW force 400 kN and the right picture shows the individual row forces up to 40 ms. The different ratings of the two metrics are showing no step effects. However a higher load spreading can be seen which is explainable due the barrier model.

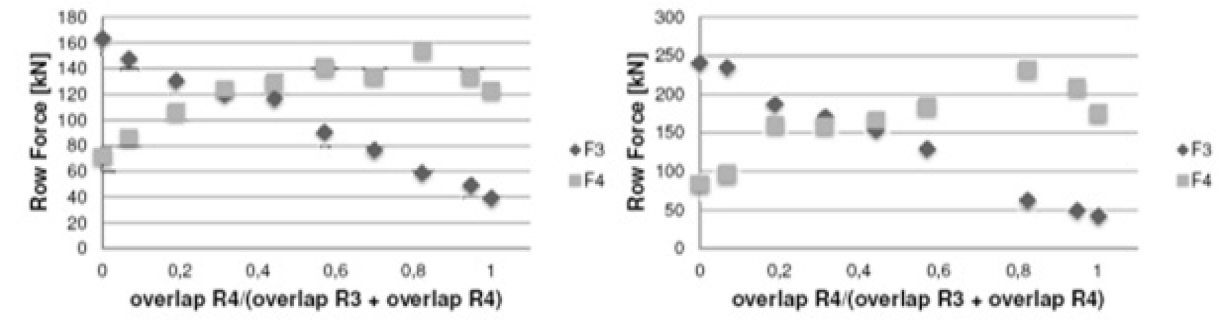


Figure 4.25: Influences of ride height on load spreading in Row 3 and Row 4 (FWDB), left graph shows the row forces up to LCW force 400 kN, right graph shows the row forces up to 40 ms.

Car-to-Car Crash Tests

In a next step car-to-car crash tests were performed. Referred to the FWRB tests results the following three configurations were chosen:

- Lowered vehicle that fails the metric against basis model (vertical offset = -40mm)
- Raised vehicle that fails the metric against basis model (vertical offset = +60mm)
- Borderline (lowered and raised) vehicles that passes the metric but were borderline (vertical offset = 100mm)

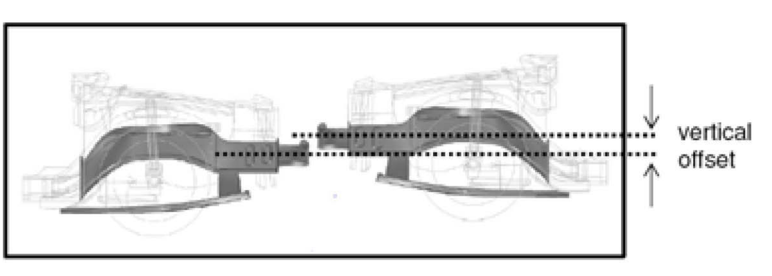


Figure 4.26: Definition of vertical offset in the car-to-car crash simulations.

These tests were conducted with 100% overlap and as well as with 50% overlap (see also Figure 4.27).

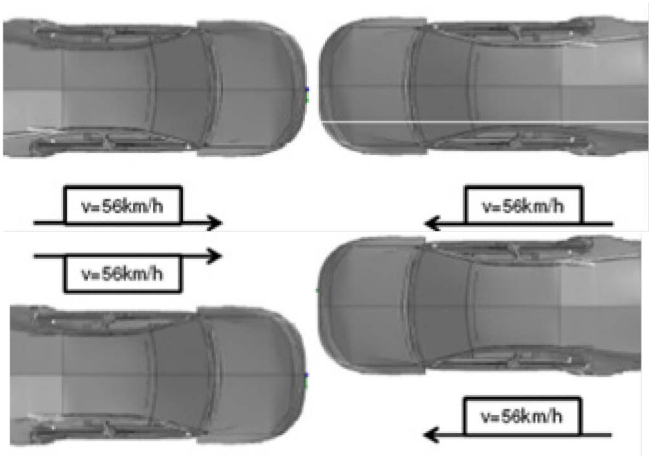


Figure 4.27: Test configuration with 100% overlap (left) and 50% overlap (right).

For the 100% overlap situation it could be seen that the overriding car has lower peak values for the deceleration of the cabin and that the intrusions of the firewall increases for the under-ridden car. These findings were confirmed by increasing the misalignment. The more the misalignment increases the more the differences of the loads increases and the incompatibility increases.

For the 50% overlap situation there were hardly any differences for the deceleration of the cabin detected. Also the intrusions at the firewall showed no trends. However, the under-ridden car shows higher a-pillar displacement then the opponent car.

Conclusions Request 7

In general the metrics seem to be robust and no step effects could be observed. The rating of the metrics correlates well with geometrical overlap of the PEAS. Intrusions and acceleration peaks indicate that crashes with “failed” vehicles are more incompatible then crashes of vehicles that passes the metric. Although the resolution of the LCW is limited to 125 mm the simulation results showed no step effects in the range of accuracy.

4.3 Conclusions

In this section a summary of the conclusions made for each of the issues will be made to give a comprehensive overview of the research taken.

Towing Hook FWRB

The simulations regarding the towing eye issues on the FWRB showed that in general the towing eye influences load cell wall readings if no filtering is applied to the load cell wall data. But if the data is filtered as recommended by the ISO standards, the small peaks are smoothed. In response to this finding the application of CFC 60 filtering is recommended to avoid undesirable influences due to hard points such as a towing eye.

Towing Hook FWDB

For the FWDB differences in the LCW readings were observed using the PCM approach and protruding towing eyes before filtering. However, applying the standard filter for load cell wall data (CFC60) the effect disappeared. In addition the influence was not observed when the standard bolt-in type was used. For FWDB the old type of towing eye could influence the metric even with a CFC60 filter. However, the bolt-in type of towing eye used on modern vehicles showed no influence with a CFC60 filter.

Variable Cross Beam Height

When the test data from Japan was analysed, one vehicle was conspicuous. This vehicle has a crossbeam attached underneath the PEAS structure and this crossbeam produced forces in Row 3 and 4 although the PEAS were partially above these two rows.

In simulation Request 1, it was investigated whether or not adequate structures in Row 3 and 4 can be mocked up in FWRB and FWDB tests. The simulation results showed that depending on the specific design of the structure it is possible to influence the metric in particular with the rigid barrier. On the other side the deformable element in the FWDB test alters the deformation pattern in a way that the real load paths can be detected. Following this the FWDB is able to detect weak structures that are not supported by stiff structures behind them. In case of a collision these weak structure are not capable to offer the opposing car a possibility to interact properly.

Cross-over Vehicles

If a vehicle will be raised in order to produce a so called "cross-over" vehicle, then it can possibly fail when the structure will not be changed in a correct manner. But to raise just the vehicle means also that there will not be enough structural alignment in a car-to-car crash. For those cars it is recommended to use secondary load paths that are placed within the common interaction zone. The question if the metrics can assess these secondary structures correctly is part of current investigations.

Step Effects

In general the metrics seem to be robust and no step effects could be observed. The rating of the metrics correlates well with geometrical overlap of the PEAS. Intrusions and acceleration peaks indicate that crashes with "failed" vehicles are more incompatible then crashes of vehicles that passes the metric. Although the resolution of the LCW is limited to 125 mm the simulation results showed no step effects.

5 DISCUSSION AND CONCLUSIONS

Starting with a review of previous work, candidate metrics and associated performance limits to assess a vehicle's structural interaction potential, in particular its structural alignment, were developed for both the FWDB and FWRB tests. Work was performed to develop a concept to assess a vehicle's frontal force matching. However, a metric has not been developed for frontal force matching because the focus was put on the development of metrics for the assessment of structural interaction in line with the FIMCAR strategy [Johannsen 2011].

- The FWDB and FWRB tests both have advantages and disadvantages. The metrics developed for these tests also have advantages and disadvantages. FIMCAR WP3 members have discussed these advantages and disadvantages and recommend that priority is given to the further development of the FWDB test and FWDB metric (3) as shown below [Figure 5.1]. However, this does not rule out the possibility of switching priority back to the FWRB test if issues are found with the deformable barrier test in the future. It should be noted that the FWRB test is already a defacto worldwide standard test and hence has an advantage from the harmonisation point of view.

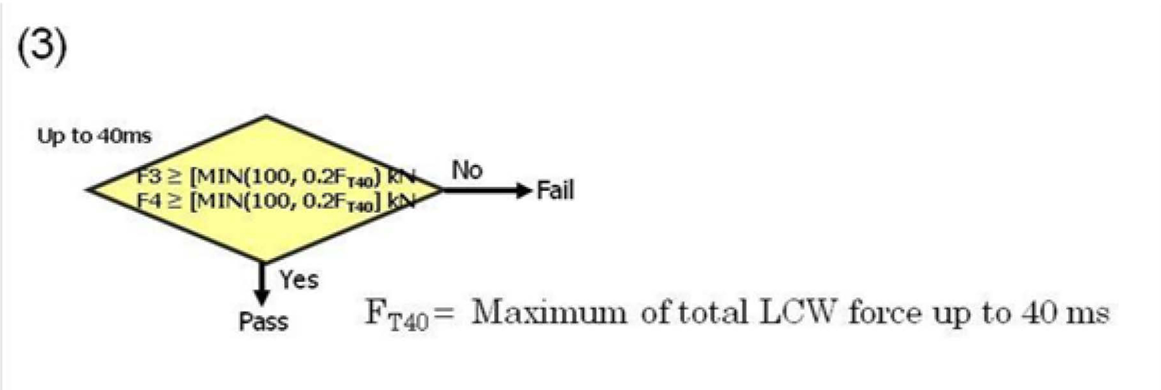


Figure 5.1: FWDB metric (3) for FWDB test.

The reasons for prioritising the full width test with the deformable element and the FWDB metric (3) are:

- The FWDB test has the edge technically over the FWRB test because there is no need for a supplementary test. Also the structural interaction assessment is made later in the impact than for the FWRB test which, because the vehicle's crash structures are more fully loaded, allows a more meaningful assessment of them. The deformable element also has the advantage that the crash loading of the structure is more representative of a vehicle-to-vehicle crash at the beginning of the impact. This is important to help ensure more realistic crash sensor triggering.
- The FWDB metric (3) is recommended because its correlation with a geometric assessment of the vehicle is as good as the other FWDB metric candidates, it is a single stage metric which follows the spirit of keeping the metric as simple as possible and effectively it allows the mass of the vehicle to be taken into account in the performance requirements.

6 ACKNOWLEDGEMENTS

The FIMCAR development of FWRB metrics was supported by JMLIT and Nagoya University by offering test data combined with the corresponding geometrical data of the respective cars and performing some calculations. Members of the FIMCAR project want to thank JMLIT and Nagoya University for their contribution.

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8 GLOSSARY

AHOF:	Average Height of Force
AHOF400:	Average Height of Force during the first 400 mm impact travel
APROSYS:	EC funded project (FP6) Advanced Protective Systems
delta-v:	velocity change following a collision
EAS:	Energy Absorbing Structures
FWDB:	Full Width Deformable Barrier
FWRB:	Full Width Rigid Barrier
GCM:	Generic Car Models
GRSP:	Working Party on Passive Safety of UNECE
KW400:	Work dissipated in the deformation between 25mm and 400 mm of crush
LCW:	Load Cell Wall
NHTSA:	US National Highway Traffic Safety Administration
ORB:	Over Ride Barrier
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PCM:	Parametric car models
PEAS:	Primary Energy Absorbing Structures
SEAS:	Secondary Energy Absorbing Structures
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility

Thorsten Adolph, Marcus Wisch, Mervyn Edwards, Robert Thomson, Mathias Stein, Roberto Puppini

FIMCAR
VIII –Full Width Test Procedure: Updated Protocol

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. Taking into account the European Enhanced Vehicle safety Committee (EEVC) compatibility and the final report to the steering committee on frontal impact [Faerber 2007] and the FP5 VC-COMPAT [Edwards 2007] project activities, two test approaches were identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

The overall objective of the FIMCAR project is to complete the development of the candidate test procedures and propose a set of test procedures suitable for regulatory application to assess and control a vehicle's frontal impact and compatibility crash safety. In addition an associated cost benefit analysis will be performed.

In the FIMCAR Deliverable D 3.1 [Adolph 2013] the development and assessment of criteria and associated performance limits for the full width test procedure were reported.

In this Deliverable D3.2 analyses of the test data (full width tests, car-to-car tests and component tests), further development and validation of the full width assessment protocol and development of the load cell and load cell wall specification are reported.

The FIMCAR full-width assessment procedure consists of a 50 km/h test against the Full Width Deformable Barrier (FWDB). The Load Cell Wall behind the deformable element assesses whether or not important Energy Absorbing Structures are within the Common Interaction Zone as defined based on the US part 581 zone. The metric evaluates the row forces and requires that the forces directly above and below the centre line of the Common Interaction Zone exceed a minimum threshold.

Analysis of the load spreading showed that metrics that rely on sum forces of rows and columns are within acceptable tolerances. Furthermore it was concluded that the Repeatability and Reproducibility of the FWDB test is acceptable.

The FWDB test was shown to be capable to detect lower load paths that are beneficial in car-to-car impacts.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of vehicle safety in frontal collisions compatibility (which consists of self and partner protection) between opponents is crucial. Although compatibility has been analysed worldwide for over 10 years, no final assessment approach has been defined to date. From the European Enhanced Vehicle safety Committee (EEVC) compatibility and frontal impact working group (WG15) [Adolph 2013] and the FP5 VC-COMPAT project activities [Thompson 2013], two test approaches have been identified as the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. In addition another procedure (a test with a moving deformable barrier) is getting more attention in current research programmes.

Within the FIMCAR project off-set, full overlap and MDB test and assessment procedures will be developed further with the ultimate aim to propose a compatibility assessment approach. This should be accepted by a majority of the involved industry and research organisations. The development work will be accompanied by harmonisation activities to include research results from outside the FIMCAR consortium and to disseminate the project results early, taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to report on the performed full overlap tests and simulation results and the development and validation of the final FIMCAR full overlap assessment procedure.

1.3 Structure of this Deliverable

The deliverable starts with a brief description of the past activities before FIMCAR and of the beginning of FIMCAR towards the development of a full overlap assessment procedure. This section is followed by a summary of the tests and simulations that were performed in the framework of the FIMCAR project. Based on these test and simulation results the FWDB assessment procedure is further developed in Chapter 4. Special emphasis is put on an improved metric that better addresses the benefits from lower load paths, the definition of the test severity and the assessment of load spreading. Chapter 5 summarises the activities to develop requirements for the load cells and the Load Cell Wall. Finally, Chapter 6 addresses the validation of the FWDB test procedure with focus on repeatability and reproducibility as well as load spreading of the deformable element.

The proposed Load Cell Specification and Calibration procedure is attached in Annex A, the proposed Load Cell Wall Specification and Certification procedure is attached in Annex B. Finally the FIMCAR FWDB Assessment Procedure is attached as Annex C.

2 TESTING AND SIMULATION

The main structural interaction problems identified in the FIMCAR accident analyses [Thompson 2013] were under/overriding, low overlap and the fork effect. In order to address the under/overriding aspect of structural interaction, structural alignment was considered as a necessary but not totally sufficient first step [Yonezawa 2009]. To address structural alignment, it was decided to use the approach that all vehicles should have crash structures in alignment with a common interaction zone. The US voluntary commitment for a common vertical interaction zone [Barbat 2005] was considered as a good starting point. A further step to address under/overriding is load spreading in the vertical direction. This can be achieved with vehicles that have multi-level load paths and strong connections between them. Load spreading in the horizontal direction is also an important factor for prevention of the fork effect and addressing accidents with small overlap. Strong cross beams can help provide good interaction in accidents with narrow objects and cross beams extending outboard from longitudinal members can improve structural interactions in cases with small overlap at the corners.

To assess structural interaction, the approach proposed in FIMCAR is that structural alignment in the vertical direction is assessed with a full width test using a Load Cell Wall (LCW). At the same time a small step towards the assessment of vertical load spreading can be achieved. It is proposed that this will be achieved using the **'common interaction zone' (CIZ)** concept.

In FIMCAR Deliverable D 3.1 [Adolph 2013] for both rigid and deformable barrier full width tests, Load Cell Wall (LCW) data was investigated as the method to assess the structural interaction characteristics of a vehicle by measuring the LCW force distribution. The current defacto standard for an LCW is one that consists of 125 mm square elements with the bottom row mounted with an 80 mm ground clearance (Figure 2.1).

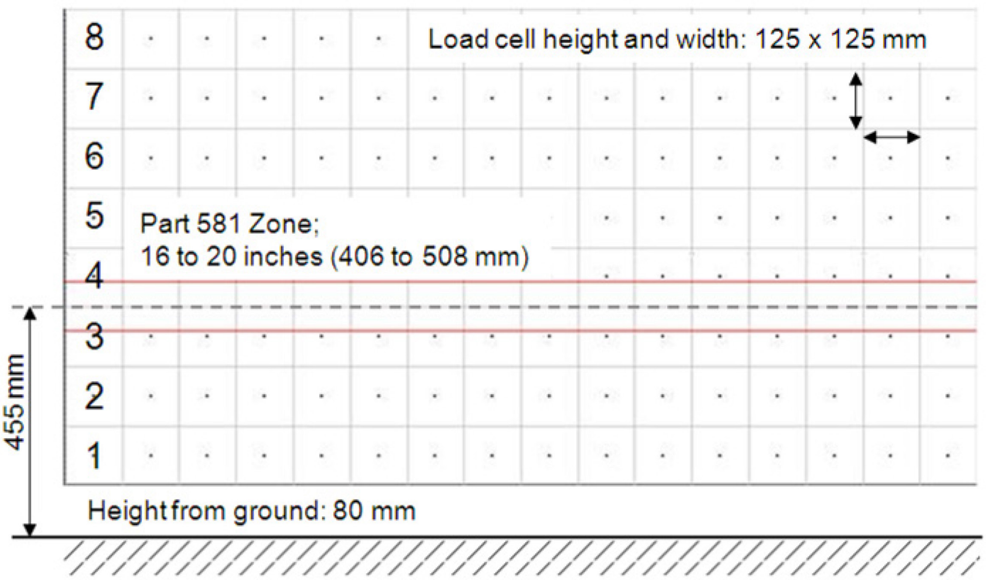


Figure 2.1: Overview of the specifications of the LCW.

In FIMCAR Deliverable D 3.1 global initiatives or strategies were reviewed that could be incorporated into a new test or assessment procedure and thus promote harmonisation of vehicle safety requirements. A significant activity that was initiated by the automotive industry is the US voluntary commitment [Barbat 2005]. This was developed to ensure that Light Truck Vehicles (LTVs) have structure in alignment with a common interaction zone from 16 to 20 inches (406 – 508 mm), further named as "Part 581 zone" measured vertically from the ground to enable better interaction with cars. The US voluntary commitment states that all LTVs sold by participating manufacturers in the US should fulfil one of the two options below (see also Figure 2.2):

OPTION 1

The light truck's primary frontal energy absorbing structure (PEAS) shall overlap at least 50 percent of the Part 581 zone (Option 1a)

AND at least 50 percent of the light truck's PEAS shall overlap the Part 581 zone (Option 1b)

OPTION 2

If a light truck does not meet the criteria of Option 1, there must be a secondary energy absorbing structure (SEAS), connected to the primary structure, whose lower edge shall be no higher than the bottom of the Part 581 bumper zone.

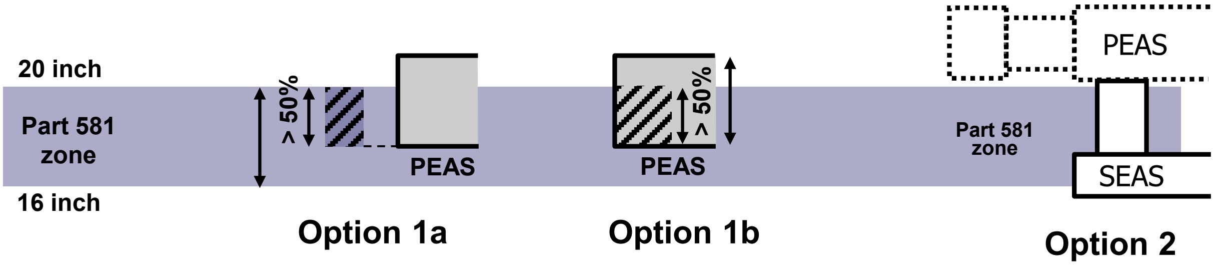


Figure 2.2: US voluntary commitment for improved compatibility of LTVs [Yonezawa 2012].

The US voluntary commitment is not desirable for regulatory application because ideally regulations should be 'performance based' and the voluntary commitment is 'design based'. A design based requirement is generally more restrictive for the layout of a vehicle and hence is less desirable for regulatory application. However, accident data analyses from the IIHS [Teoh 2011] and NHTSA [Greenwall 2012] have shown that the introduction of the US voluntary commitment has helped to reduce casualties in LTV-to-car crashes. But it could not be definitely said that this improvement is due to the PEAS and SEAS requirements or due to general improvements in safety.

Given this information, it is important for FIMCAR to incorporate some of the concepts of this informal standard as it provides both a benefit and a potential for acceptance in jurisdictions outside of Europe.

3 SUMMARY OF TESTS AND SIMULATIONS PERFORMED

In total eleven full width tests were planned in Work Package 3. These tests were meant to provide additional data for the development of the metric and also to provide data to analyse repeatability and reproducibility of the proposed test and assessment protocol. Car-to-car tests were performed in Work Package 6 and are described in FIMCAR Deliverable D 6.1 [Sandqvist 2013]. Nevertheless as some of the results of these car-to-car tests are very important for the development of the full width test, key results are described in Chapter 6.1.2. In addition to the full width tests component tests were planned and conducted to investigate the performance of the load cell wall and the deformable barrier face. Due to the cooperation with Japan within the FIMCAR project three additional full width tests were conducted by JAMA to answer questions which came up during the project.

The matrix in Table 1 gives an overview of the tests performed in Work Package 3. As the tests were performed by different institutions, a template was developed to make sure that the analyses were done in the same way. Reports for all the tests can be found in Annex D: Full Width Test Reports.

Table 1: Test matrix of full scale, sled and component tests conducted in work package 3.

Purpose	No.	Kind of testing	Laboratory	Vehicle Type	Test date CW/YY	Status	Barrier FWRB	Barrier FWDB	Test speed (km/h)	Dummy choice *with ribeye HIII 50% male	Dummy choice *with ribeye HIII 5% female
Repeatability / Reproducibility	1	Full scale	BASt	Supermini 1	09/12	DONE		x	56	Front left*	Front right*
	2	Full scale	BASt	Supermini 1	10/12	DONE		x	56	Front left*	Front right*
	3	Full scale	FIAT	Supermini 1	47/11	DONE		x	56	Front left	Front right
Further Validation / Robustness	4	Full scale	IDIADA	Supermini 1	33/11	DONE		x	56	Front left	Front right
	5	Full scale	PSA	Supermini 1	33/11	DONE		x	56	Front left	Front right
	6	Full scale	IDIADA	Supermini 2	25/11	DONE	x		50	Front left	Front right
	7	Full scale	Renault	City Car 1	32/11	DONE		x	56	Front left	Front right
	8	Full scale	FIAT	Supermini 2	38/11	DONE		x	56	Front left	Front right
	9	Full scale	TRL	SUV 1	12/12	DONE		x	56	Front left*	Front right*
	10	Full scale	BASt	Small Family Car 1	17/12	DONE		x	50	Front left*	Front right*
	11	Full scale	BASt	Supermini 2	24/12	DONE		x	40	Front left*	Front right*
	12	Full scale	IDIADA	SUV 2	36/12	DONE		x	56	Front left	Front right
	13										
Tests external partners	14	Full scale	JAMA	K-Car 1	46/11	DONE		x	55	Front left	Front right
	15	Full scale	JAMA	SUV 3	14/12	DONE		x	55	Front left	Front right
	16	Full scale	JAMA	K-Car 2	39/11	DONE		x	55	Front left	Front right
Component tests / Load spreading on load cell measurements	17	Sled Test	BASt		22/11	DONE	x		15	-	-
	18		BASt		22/11	DONE	x		15	-	-
	19		BASt		22/11	DONE	x		15	-	-
	20		BASt		22/11	DONE	x		20	-	-
	21		BASt		22/11	DONE	x		25	-	-
	22	Component	TRL		24/11	DONE		x	40	-	-
	23		TRL		24/11	DONE		x	40	-	-
	24		TRL		24/11	DONE		x	40	-	-
	25		TRL		24/11	DONE		x	40	-	-
	26		TRL		24/11	DONE		x	40	-	-
	27	Component	BASt		June 2010	DONE			static	-	-

3.1 Full Width Tests

In total twelve full scale tests against the FWDB or FWRB were performed in FIMCAR. Three additional tests from JAMA were performed to further investigate the metrics and the FWDB. All tests were conducted with the HIII 50% dummy on the driver side and the HIII 5% female dummy on the passenger side. This consistency was necessary to compare the data.

Additional instrumentation with regard to the chest loading were added in some full scale tests. Therefore, BASt offered their RibEye measurement system to use it in FIMCAR tests in order to gain a better understanding of the thorax loading in high acceleration tests.
The objectives of the tests are described in the following sections. Test reports are in included in Annex D. The individual results of the tests were used in different ways and are mainly part of Chapter 4.

3.1.1 R&R Analyses with Supermini 1

Three full scale tests with the Supermini 1 were performed at two different test labs (FIAT and BASt). These tests were used to add additional data for the Repeatability and Reproducibility analyses of the full width deformable barrier test procedure. The height and the weight of the test vehicles were adjusted so that they had the same ride height. The Supermini 1 was selected because this is a single load path vehicle which is a worst case situation in terms of repeatability. The longitudinals of the vehicle are located mainly in LCW Row 4. However, it is still in alignment with the US voluntary agreement. The dummy selection was HIII 50 % on the driver seat and HIII 5 % on the front seat passenger seat.

The test reports can be found in Annex D, the results of these tests are discussed in Chapter 6.1.1.

3.1.2 Raised and Lowered Supermini 1

Two full scale tests with a raised (at PSA) and a lowered Supermini 1 (at IDIADA) were performed in order to investigate the sensitivity of the metric. The raised Supermini 1 had the longitudinals just slightly above the common interaction zone which means that it should not pass the metric. The lowered Supermini 1 was conducted at IDIADA and had the longitudinals still in the common interaction zone. In FIMCAR a series of car-to-car tests with Supermini 1 cars in aligned and non-aligned conditions was conducted in order to compare the performance.

The test reports of the FWDB tests can be found in Annex D, the results of these tests are discussed in Chapter 6.2.

3.1.3 Vehicles with far Forward Lower Load Path

Two vehicles were tested to answer the question if vehicles with a far forward lower load path would be discriminated by the full width metric developed. City Car 1 was selected and tested at Renault and a Supermini 2 was selected and tested at Fiat.

The test reports can be found in Annex D, the results of these tests are discussed in Chapter 6.1.3.

3.1.4 SUV with and SUV without a Lower Load Path

The performance of SUVs with different structural concepts was investigated with car-to-car tests in Work Package 6. Three vehicles were selected: SUV 1, Small Family Car 1 and a SUV 2. These vehicles were also tested against the full width deformable barrier to check how the vehicles perform with the developed metric.

Side impact tests and front and side impact simulations were carried out with SUV 3 and Large Family Car 1 with different load path configurations on SUV 3. Simulations for the vehicles in the FWDB were performed to investigate their performance with the proposed metrics.

The test reports can be found in Annex D, the results of these tests are discussed in Chapter 6.1.2. Car-to-car tests are further documented in Deliverable 6.1 [Sandqvist 2013].

3.1.5 Comparison of different Test Speed

The test speed for both full width test procedures was carefully selected in Work Package 3. Analyses of accident data have shown that a test speed of 50 km/h would be appropriate for AIS 3 injury levels and 35 to 40 km/h were appropriate for AIS 2 injury levels. However, FIMCAR relied on analysis of pre-existing test data in addition to the FIMCAR tests. The pre-existing tests were usually performed at 56 km/h (or 55 km/h in JNCAP test). Therefore a Supermini 2 test against full width rigid barrier was performed with 50 km/h and a Supermini 2 test against full width deformable barrier was performed at 40 km/h to investigate if changes in the metric were necessary.

The test reports can be found in Annex D, the results of these tests are discussed in Chapter 1.1.1.

3.2 Component Tests

There were a number of component tests conducted during the FIMCAR project. These results were mainly used to answer questions regarding the load spreading of the deformable element and the performance of the load cell wall.
The next chapters were meant to give an overview of all component tests performed.

Further results are discussed in Chapter 4 and Chapter 6.3.

3.2.1 LCW Dynamic Calibration Tests

The objective of these trolley tests was to investigate if a dynamic load cell test is needed for the certification and specification procedure. Following this a crash test trolley was used with a stiff front plate crashing against aluminium honeycomb barriers and measuring the forces with an LCW. The objectives of these five tests were to investigate the repeatability of forces in different load cells, analyse the influence of protective coverings for load cells (wood plate) and analyse the influence of increasing test speed on load cell forces, acceleration and deformation.

The test report can be found in Annex D, the results are discussed in Chapter 6.3.

3.2.2 Sled Tests to investigate Load Spreading

The objective of this component work was to determine the reasons for the unexpected differences in peak loads seen between individual load cells. This was done by TRL by performing additional component tests to investigate whether the aluminium backing plate or the interface between the two layers affects distribution of load between cells.

The tests and the outcome are reported in Chapter 6.3.

3.2.3 Load cell Tests with Excentric Loading

For the development of the certification and specification of the load cells additional component tests were necessary to investigate the performance of different load cells in eccentric loading conditions. As a starting point two load cells from BASt were calibrated in a more advanced way than before. Based on these results it becomes obvious that additional tests from further test laboratories were needed. Thus, load cells from IDIADA, TRL, BASt and Japan were sent to Humanetics to perform these tests

The development of the certification and specification protocol for the load cells and the tests performed are explained in Chapter 5.2.1.

3.3 Simulations

To support the investigations of WP 3 a large number of simulations was conducted by WP 5. Main objective of these simulations was to validate the test results and assessment procedures. Furthermore specific analyses were conducted to investigate the influence of the front end structures on the compatibility metrics. Most of the simulation work was already described in FIMCAR Deliverable D3.1 [Adolph 2013]. Therefore a short description of these analyses is presented in this chapter. The analyses of the simulations will be discussed in the development chapter (Chapter 4) or validation chapter (Chapter 6).

3.3.1 Variable Crossbeam Heights

Main objective of this analysis was to investigate the influence of a PEAS design where the cross beam and the longitudinal were not in vertical alignment. For that reason five modifications of the PEAS were modelled and the effect on the assessment criteria were investigated.

Within the analyses for the FWDB following remarkable observations were made:

- The wall force limit for 400 kN was reached after a later time (37 ms versus 44 ms), whereby no engine dump occurred.
- The basic model fulfils the requirements for all proposed metrics.
- The modification 2 (lowered cross beam) also fulfils the requirements of the metrics while this was not the case for the other modifications.

For more details see FIMCAR Deliverable D3.1 [Adolph 2013]).

3.3.2 Influence of Towing Eye

Goal of this study was to analyse the effect of hard points located in the front end on the metrics. In partial the towing eye respectively the towing eye attachment was analysed in FWRB and FWDB crash configurations.

The most important conclusion was that the deformation pattern of the EAS differs depending on the test procedure. While the effect of these very stiff structures disappeared in the FWRB test after applying a CFC60 filter (which is the standard filter for such a channel) the towing eye had an influence to the wall force in the FWDB test. However, the results of the simulation with the towing eye attachment showed not influence on the assessment metrics in both crash configurations. Additional simulations were done with the GCM models from CRF. These analyses support the results from the PCM models.

For more details see FIMCAR Deliverable D3.1 [Adolph 2013].

3.3.3 Effect of Cross-Over Vehicles

The objective was to simulate cross-over vehicles in order to investigate the effect of differences in ride heights according to FWB assessment criteria. Simulations were conducted with the Parametric Car Model (Large Family Car) which is tested against the FWRB and the FWDB. The cross-over version is modified by a horizontal offset of the barrier of 60 mm.

Main finding of this analysis was that a raised vehicle could fail the assessment metrics of both test procedures. This means only to raise the vehicle and its structures will decrease the structural interaction in car-to-car crashes.

For more details see FIMCAR Deliverable D3.1 [Adolph 2013].

3.3.4 Investigation of Step Effects

To check the metrics for step effects a set of car-to-FWB and car-to-car simulations was conducted. The objective of this analysis was to investigate the robustness of the metrics in terms of step effects and to ensure the correct assessment of the metrics. Furthermore the results of the FWB tests should be verified in car-to-car simulations.

The outcome of this investigation was that the wall force depending criteria correlate well with the most relevant crash structures. No step effects could be observed in both test procedures. The results of the car-to-car simulations showed that the vertical misalignment of the PEAS lead to lower peak values for the deceleration but the intrusion increased.

For more details see FIMCAR Deliverable D3.1 [Adolph 2013].

3.3.5 SEAS Analyses

The Objective of this study was to investigate the influence of the SEAS in car-to-car crashes and to identify characteristics of appropriate SEAS that are able to improve structural interaction. Therefore geometrical modifications in terms of varied stiffness and SEAS positions were done. First the modified PCM models were crashed in an adapted ORB test to identify the force level of the SEAS. Furthermore this test configuration should be checked, if it is able to assess a SEAS in a correct manner (provide benefits in car-to-car crashes). After that the PCMs were run against the FWRB and FWDB with 50 km/h. The main objective was to check if the SEAS could be detected on the LCW.

3.3.5.1 **First Modifications**

Figure 3.1 shows the baseline configuration of the used PCM (Large Family Car, LFC). The PEAS are in alignment with Row 3 and 4 and the SEAS are in alignment with Row 2.

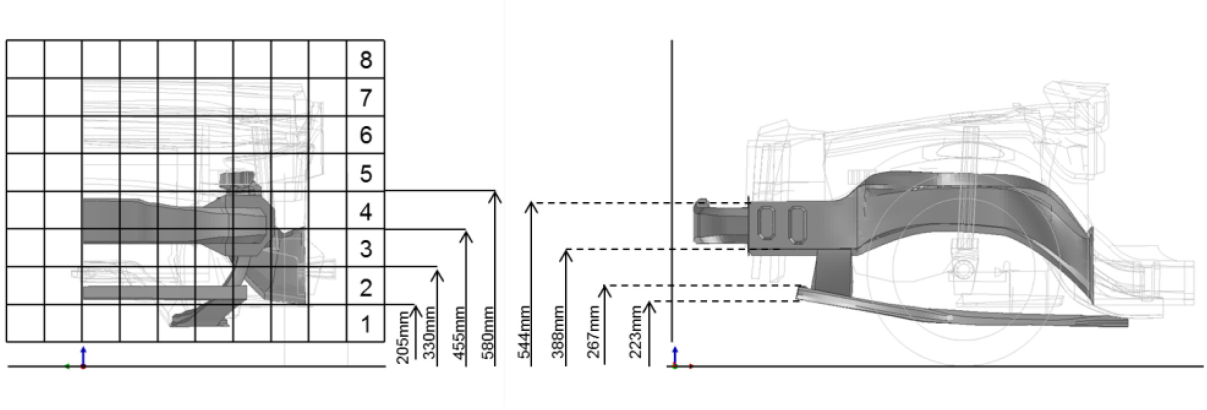


Figure 3.1: Baseline configuration of the PCM (LFC).

As a first step the position of the SEAS in x-direction was modified, see Figure 3.2. Former simulation with a modified FORD Taurus model indicated that an appropriate SEAS will bring benefits if it is located between 180 mm and 400 mm behind the cross beam [Park 2009]. This modifications only affected the longitudinal and the cross beam of the SEAS. The position of the vertical connection was not changed in the first step.

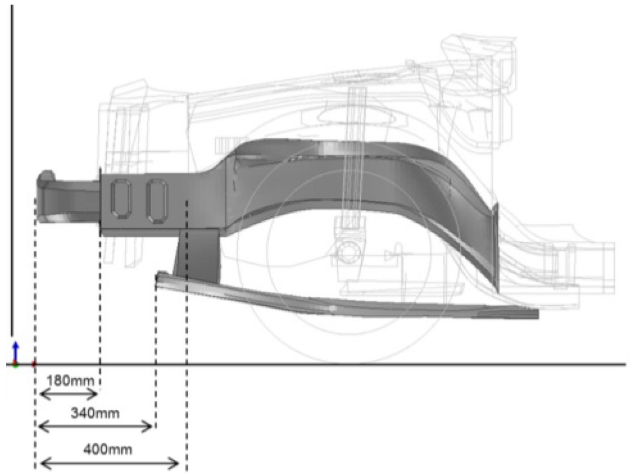


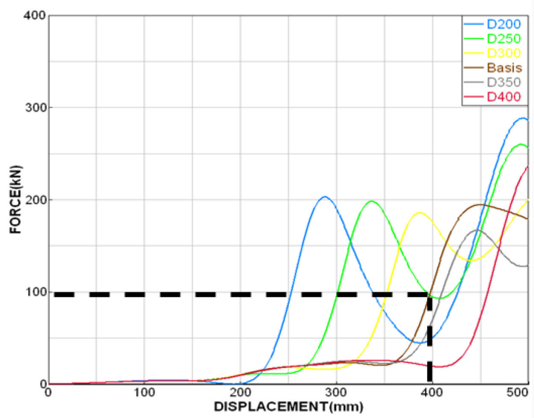
Figure 3.2: Upper and lower boundaries of the first SEAS modifications.

In total five modifications were modelled (in addition to the baseline model):

D200 → SEAS 200 mm behind cross beam
D250 → SEAS 250 mm behind cross beam
D300 → SEAS 300 mm behind cross beam
D350 → SEAS 350 mm behind cross beam
D400 → SEAS 400 mm behind cross beam

3.3.5.2 **ORB Simulations**

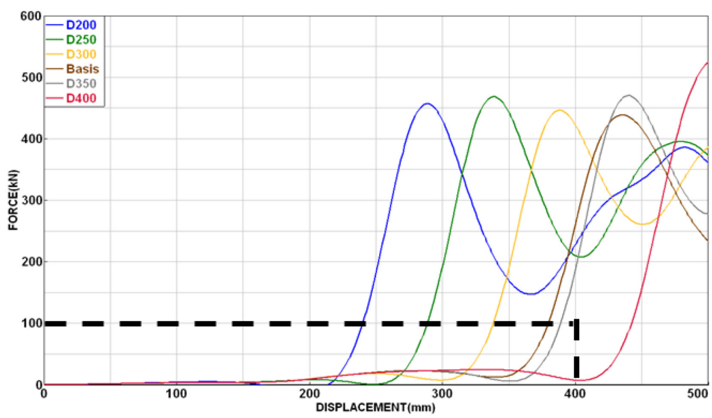
The six models were crashed against the ORB with 40 km/h. The results are shown in Figure 3.3. The analysis showed that depending on the SEAS location the vehicle was able to pass the ORB criterion (D200; D250; D300). If the lower load path is located further rearward the structure was not able to apply 100 kN within 400 mm displacement (Basis; D350; D400).



Modification	s @ F_{max} [mm]	F_{max} [kN]
D200	288	203
D250	337	198
D300	387	186
Basis	400	73
D350	400	68
D400	400	26

Figure 3.3: Simulation results of ORB crashes.

As already figured out in the PDB simulations [Lazaro 2013] the sub frame was relative weak. Due to this only the far forward SEAS could apply enough forces to the ORB. A second run was conducted with reinforced SEAS (stiffness increased by factor 2).



Modification	s @ F_{max} [mm]	F_{max} [kN]
D200	288	457
D250	338	468
D300	388	446
Basis	400	257
D350	400	183
D400	331	25

Figure 3.4: Simulation results of ORB crashes with reinforced subframes.

Figure 3.4 shows the results with the reinforced sub frame. All modifications, except D400, pass the ORB test. Due to the very stiff structure the force increase very fast and to a relative high level.

Following the intention of the ORB test to check SEAS on vehicles that do not meet the US volunteer agreement Options 1a and 1b, the results indicate that all modification should bring benefits in car-to-car crashes.

3.3.5.3 **FWRB and FWDB Simulations**

To check if the SEAS structures can be detected in FWRB and FWDB test all modifications (initial stiffness of SEAS and reinforced SEAS) were crashed against both barriers with 50 km/h.

Figure 3.5 and Figure 3.6 show exemplarily the row forces and the sum forces for the simulations with the reinforced sub frame against FWRB and FWDB with 50 km/h. The red circles mark the maximum forces applied to Row 2. The reinforced SEAS apply very high forces to the wall, in particular to the FWRB, which is unrealistic compared to real cars but highlighted the effect on the LCW readings due to the SEAS.

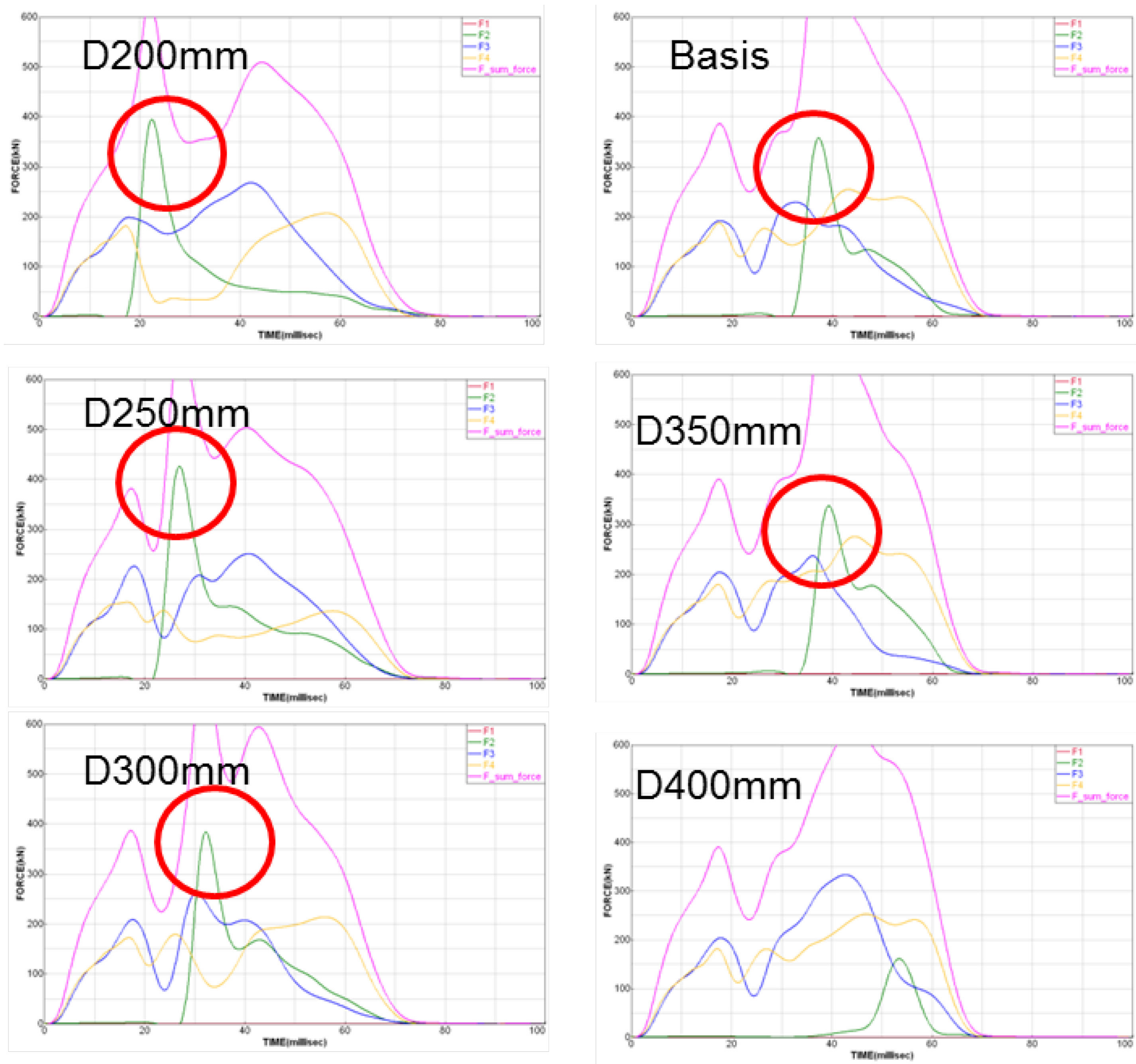


Figure 3.5: Simulation results of FWRB test with reinforced sub frame.

The main findings for the FWRB configurations were:

- Sub frames in modifications D200 to D350 could be detected
- Force levels measured in Row 2 are on same level for modifications D200 to D300
- Depending on the position of the SEAS the maximum forces were applied in different points of time but too late in the impact (after total forces reached 200 kN)

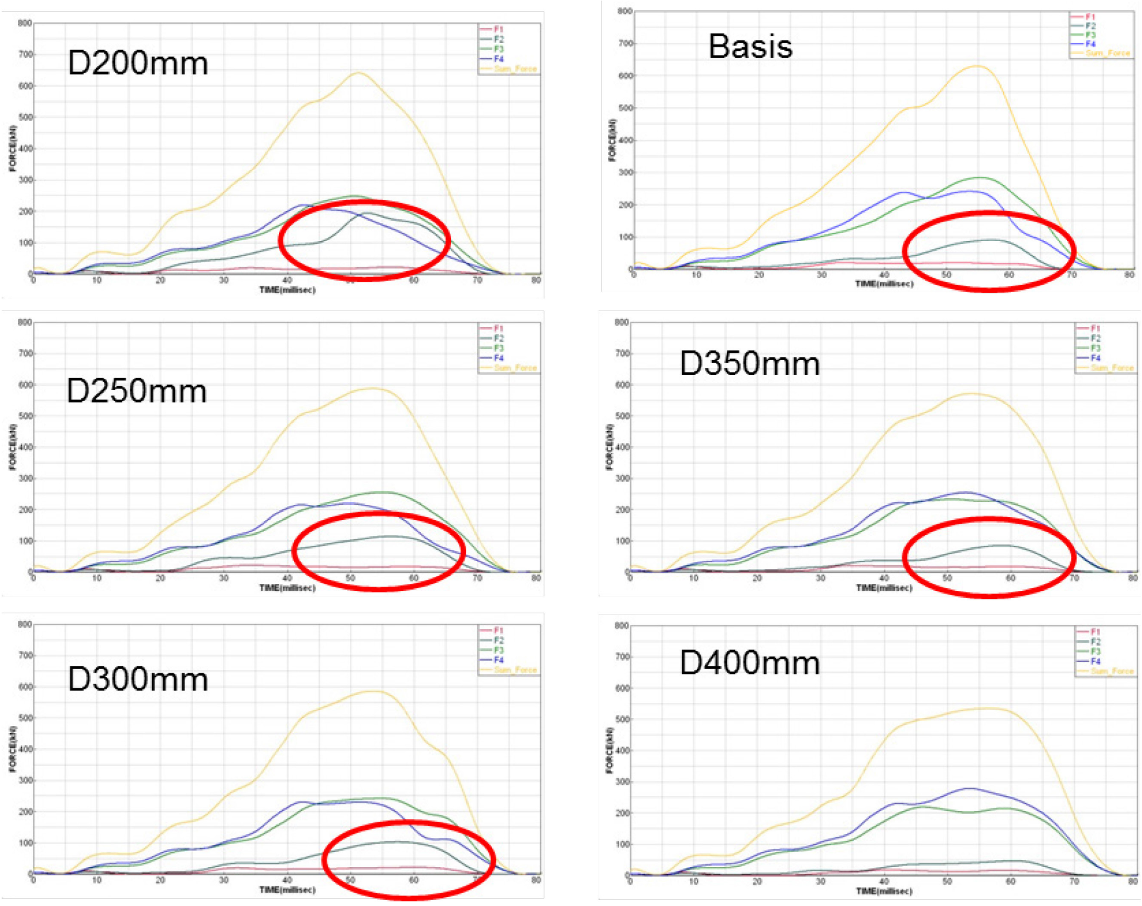


Figure 3.6: Simulation results of FWDB test with reinforced sub frame.

The main findings for the FWDB configurations were:

- Sub frames in modifications D200 to D350 could be detected
- Due to the load spreading of the honeycombs forces are also applied to Row 1
- Reinforced sub frames applied higher forces but too late in the impact (after 40 ms)

3.3.5.4 **Car-to-Car Simulations**

To analyse the modifications in car-to-car crashes the modified LFC was raised by 70 mm and crashed (both vehicles 56 km/h, 50% overlap with respect to the bullet vehicle) against the baseline super mini, large family car and the executive car, see Figure 3.7. These three bullet vehicles pass the FWB metrics in their baseline configuration.

The results of this investigation showed that the SEAS did not affect the structural interaction of the two cars in all configurations. The main reason for that is that the SEAS of both cars did not meet during the crash or interact just a short moment. This also counts for the configurations where the SEAS should meet the colliding PEAS.

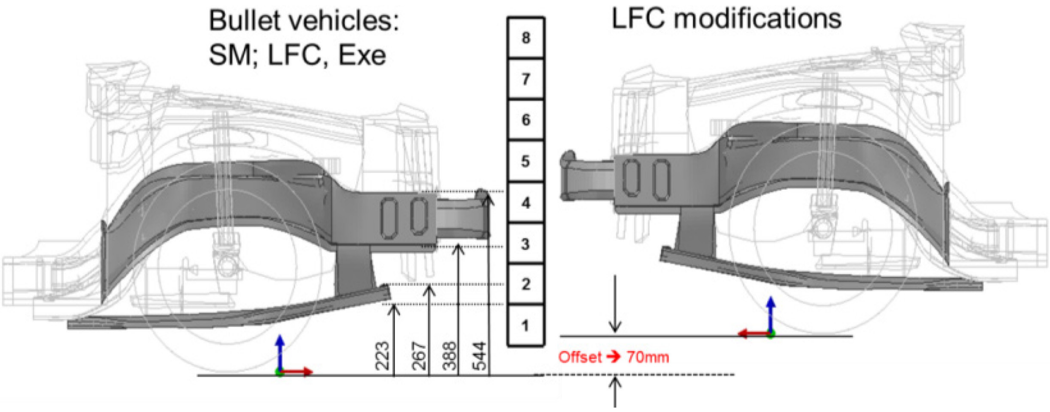


Figure 3.7: Car-to-car configurations with first modifications

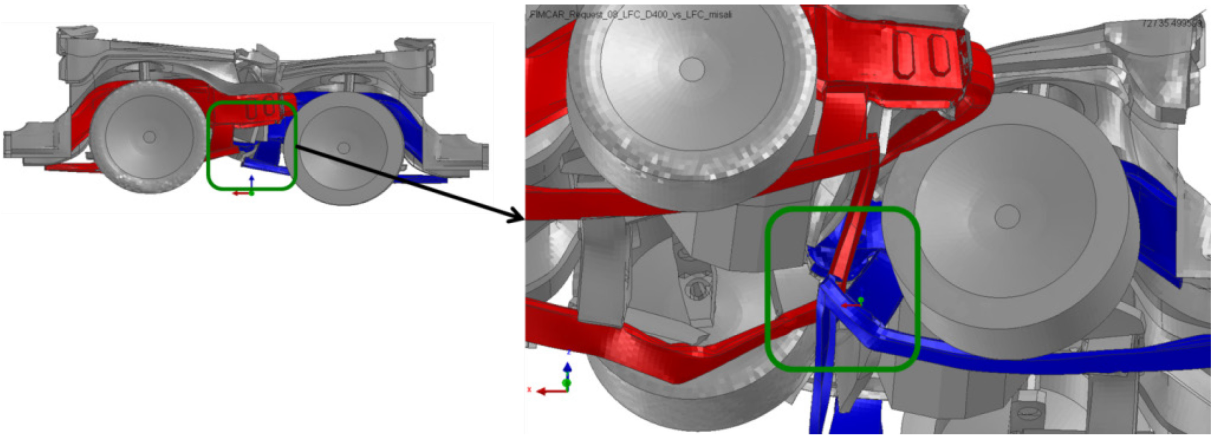


Figure 3.8: Simulation results of car-to-car crash (D400 red; LFC blue).

As highlighted in Figure 3.8 the results indicated that the vertical connection between the SEAS and the PEAS offers a good support to the penetrating structures. In almost every case the SEAS were not activated before they meet this vertical connection. Because this part was not modified it was located very far rearward.

3.3.5.5 **Summary of First Modifications**

The conducted simulations showed that the ORB test does not discriminated between appropriate (provides benefits in car-to-car crashes) and inappropriate SEAS. Thus the ORB test produces “false positives” which means that the test assess a cars structure as good while the car-to-car test showed no improvements in the structural interaction.

Based on the results of the car-to-car simulations that the vertical connection between PEAS and SEAS can bring benefits in car-to-car crashes additional modifications were done.

3.3.5.6 **Second Modifications**

To analyse the effects of a far forward located vertical connection on car-to-car crashes two further modifications were modelled. Based on the baseline LFC model, that was raised by 60 mm to align it with Row 4 (raised baseline LFC fails the metrics), the vertical connection as well as longitudinal and cross beam of the SEAS were moved forward and the cross section of the cross beam was increased, see Figure 3.9.

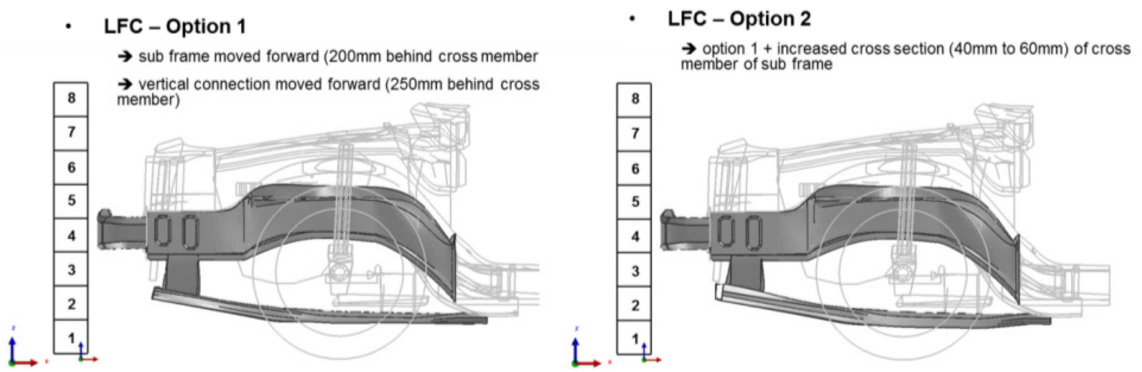


Figure 3.9: Second LFC modifications (vehicles were raised by 60 mm to align them with Row 4).

The following four models were used for this analysis:

LFC baseline	(passes all metrics)
Raised LFC	misaligned with Row 4
LFC – Option 1	subframe 200 mm and vert. connect. 250 mm behind cross beam
LFC – Option 2	option 1 + increased cross section (40 mm to 60 mm)

All modifications were run against the FWDB with 50 km/h. For the analysis two assessment metrics including the new proposal taken into account a limit reduction due to forces applied in Row 2 were used, see Chapter 4.1. Table 2 and Table 3 show the results of the FWDB test with 50 km/h. The raised LFC and the modifications fail both metrics. Although, the intention of the second metric is to promote lower paths the modifications were not able to apply enough forces. The main reason for that is that the limit reduction criteria (70 kN) were defined with respect to 56 km/h collision speed, while the simulations were conducted with 50 km/h. Taking into account the results of the analysis of the test severity, see Chapter 3.3.6 the forces applied to the wall will decrease with reduced collision speed.

Table 2: Simulation results with FWDB 50 km/h of second modifications (metric without Limit Reduction).

Current Metric			
	Misaligned (aligned row 4)	**Option 1** (subframe and vertical connection far forward)	**Option 2** (subframe cross section increased and vertical connection far forward)
F_{sum} [kN]	458	427	467
$0.2F_{sum\_@\_40ms}$ [kN]	91,6	85,4	93,4
F_4 [kN]	190	146	155
F_3 [kN]	61	66	81
F_2 [kN]	32	46	63
	fail	fail	fail

Table 3: Simulation results with FWDB 50 km/h of second modifications (LR metric).

Limit Reduction Metric			
	Misaligned (aligned row 4)	**Option 1** (subframe and vertical connection far forward)	**Option 2** (subframe cross section increased and vertical connection far forward)
F_{sum} [kN]	458	427	467
F_4 [kN]	190	146	155
F_3 [kN]	61	66	81
$F_3 + F_4$ [kN]	251	212	236
$0.4F_{sum\_@\_40ms}$ [kN]	183,2	170,8	186,8
$0.2F_{sum\_@\_40ms}$ [kN]	91,6	85,4	93,4
F_2 [kN]	32	46	63
LR [kN]	(-38 → 0)	(-24 → 0)	(-7 → 0)
	fail	fail	fail

The last step was the analysis of the performance of the modifications in car-to-car crashes. Figure 3.10 shows the geometrical configurations. The cars were run against each other with 56 km/h and 50 % overlap.

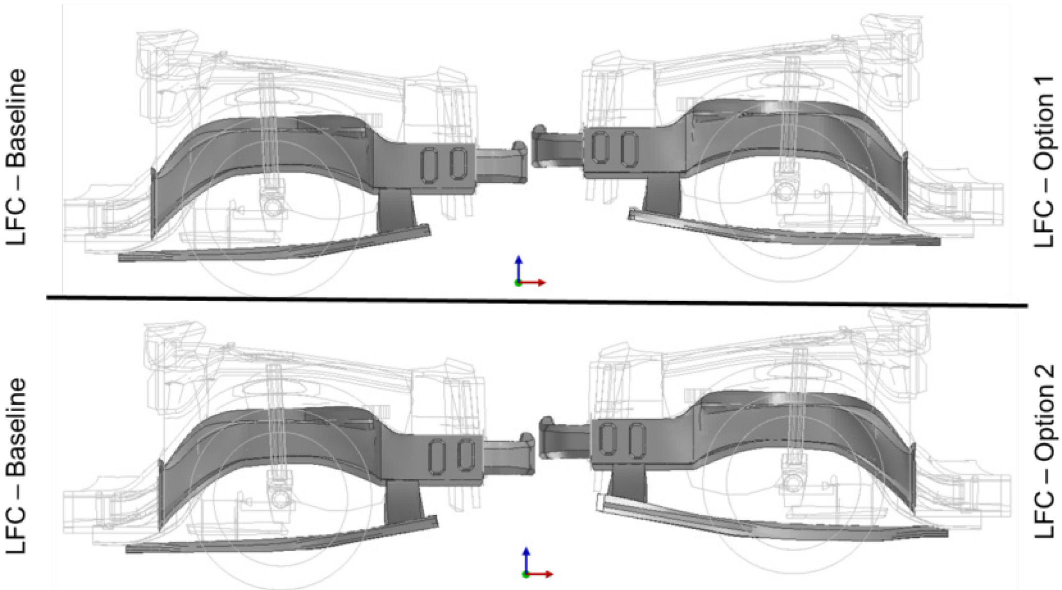


Figure 3.10: Car-to-car configurations with second modifications.

The intrusions and decelerations were analysed. Table 4 shows the measured intrusions. Even though the intrusions for the overridden car are higher (underriding car hits the opposing wheel which moves rearwards and causes the higher intrusions) the trend shows that the modifications for LFC – Options two reduces the intrusions.

Table 4: Intrusion measurements of car-to-car simulations with second modifications.

	baseline	modified car
baseline - misaligned	-125mm	-220mm
baseline - option 2	-98mm	-122mm

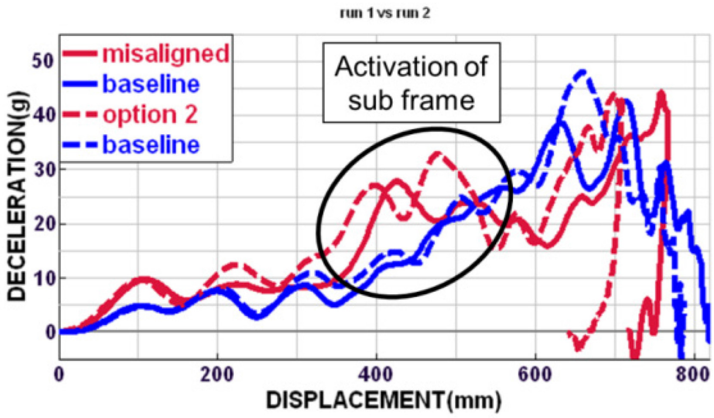


Figure 3.11: Deceleration-displacement plots of misaligned against baseline LFC and option 2 against baseline LFC.

Figure 3.11 shows the deceleration-displacement plots of the same configurations. Compared to the misaligned LFC (red graph) the LFC option 2 shows a clear peak (red dotted graph) due to the early activation of the sub frame, which indicates the improved structural interaction.

3.3.5.7 **Summary of Second Modifications**

Summarising the results of the second modifications it could be shown that a far forward located vertical connection is able to improve the structural interaction of cars which PEAS are not in alignment. However due to the fact that the limit reduction metric uses thresholds defined by analysing 56 km/h FWDB crashes the modified LFCs were not able to pass the LR metric.

3.3.5.8 **Conclusions**

The main objective of this request was to analyse the influence of SEAS in car-to-car crashes and to identify characteristics of appropriate (improve structural interaction) SEAS. The main findings were that the structural interaction was improved due to the vertical connection and the increased cross section of the sub frame, even though the modifications (LFC option 1 and LFC option 2) were not able to pass the metrics (with and without LR). The analyses also showed that the ORB test is a test procedure that is not capable to discriminate between appropriate and inappropriate SEAS. Furthermore the following SEAS characteristics were identified to bring benefits in car-to-car crashes:

- Far forward position of the sub frames cross beam
- Far forward vertical connection between SEAS and PEAS
- Large cross section to provide enough support for penetrating structures

Additional analyses for the vertical load spreading are also reported in Chapter 4.3. More details concerning PEAS and SEAS interaction can be found in Stein et al. 2013/1.

3.3.6 Different Test Speed

Based on the analysis of the test severity for full width crash test, see Chapter 4.2, simulations were conducted to check if the assessment metrics works independent from the test speed. The GCMs and the PCMs were crashed against the FWRB with 56 km/h and the FWDB with 40 km/h, 50km/h and 56 km/h. A detailed description of the investigations and the results is given in Chapter 4.2.

3.3.7 Volvo Simulations

Volvo simulation with the car models of the Large Family Car 1 and the SUV 4 were performed to add data for the development of metric and to answer open questions. The advantage of this work was that simulation with full vehicle models was done which are more detailed compared to the generic car models. The SUV 3 was simulated against the FWDB and FWRB to generate more data for the metric development and to investigate the performance of a vehicle with a high PEAS and a lower load path. In addition to this simulation with SUV 3 striking Large Family Car 1 at 50 km/h (side impact) were done.

The results are reported in Chapter 4.3.

4 FURTHER DEVELOPMENT OF FULL WIDTH DEFORMABLE BARRIER PROTOCOL

4.1 Further Development of Metric

The FWDB metric was originally developed and reported in FIMCAR Deliverable 3.1 can be summarised as follows:

- Up to time of 40 ms
  - $F4 \geq [MIN(100, 0.2F_{T40})$ kN
  - $F3 \geq [MIN(100, 0.2F_{T40}]$ kN
  - where F_{T40} = Maximum of total LCW force up to time of 40 ms

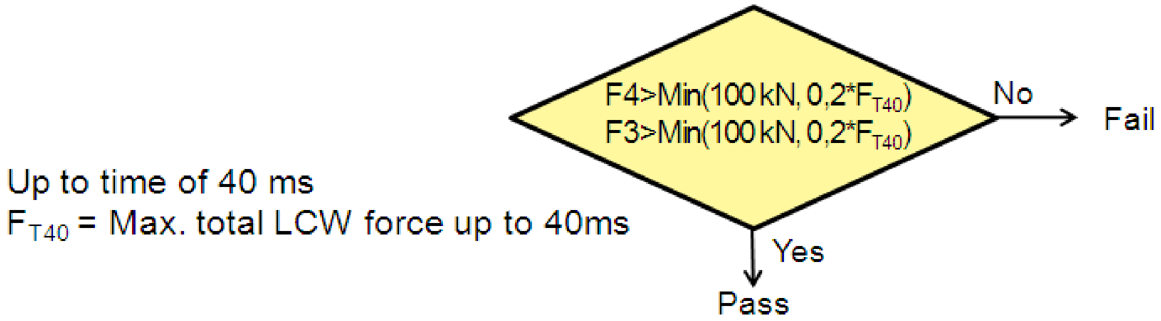


Figure 4.1: FWDB metric with forces in Row 3 and 4 up to 40 ms.

The concept of this metric is to ensure that all vehicles have adequate structure in alignment with the common interaction zone by using a minimum load requirement for Row 3 and Row 4. To ensure that light vehicles are able to meet the requirement, it is specified in terms of a fraction of the load that the vehicle applies to the wall as well as an absolute value. The absolute value is also necessary to ensure that the requirement for the strength of the SEAS for vehicles with their SEAS in alignment with the common interaction zone is not over-onerous; it is effectively limited to 100 kN.

The objective for the development of a metric modification was that it should allow designers greater freedom for the design of vehicles with lower load paths whilst still ensuring that the vehicle has adequate structure in the common interaction zone for good compatibility. This should help encourage the development of this type of vehicle which is desirable because this type of vehicle (i.e. one with load paths at multiple levels compared to a single level load path one) has been shown to have better compatibility in terms of structural interaction potential.

The concept for the metric modification was:

- Reduce the load required in Row 3 by a part of the amount of load that the vehicle's lower load path applies to Row 2.
- Still require same minimum load in Rows 3 and 4 overall to ensure that the vehicle has adequate structure in alignment with the common interaction zone.

The methodology used to develop the metric modification was:

- Determine max load that vehicles without subframes apply to Row 2.
- Subtract load that vehicles apply above this load in Row 2 from load requirement for Row 3. To ensure that the situation does not arise where there is no load (or structure) in alignment with Row 3, the limit reduction was capped at 50 kN.

Following this methodology and using the data from available tests shown in Figure 4.3 the following modified metric was developed:

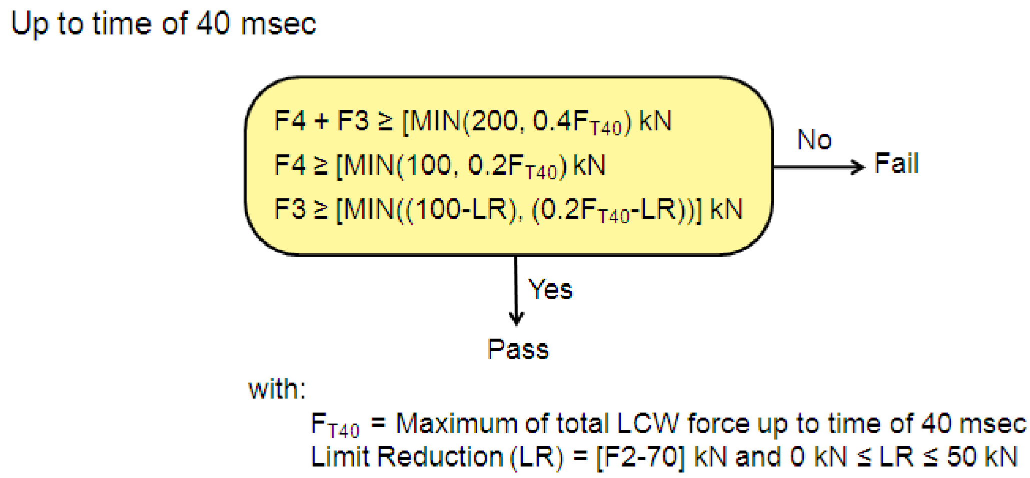


Figure 4.2: FWDB Metric with Limit Reduction.

Notes:

- Additional requirement on (Row 3 + Row 4) was needed to ensure that the overall load limit on Rows 3 and 4 remains the same as for the original metric when limit for Row 3 is reduced.
- Maximum load that vehicle without subframe applies to Row 2 is 70 kN by Nissan Micra (from Figure 4.3 which summarises currently available test data).
- The Limit Reduction (LR) is capped at 50 kN to ensure that some load is applied to Row 3 and hence that some structure is in alignment with it.
- Further validation of the proposed performance limits is recommended, in particular consideration of light cars and the influence coming from the proposed change in test speed to 50 km/h is needed.

	Smart Fortwo	Ford Fiesta	FIAT Panda	Nissan Micra	VW Golf	Opel Astra	Opel Astra 2	FIAT Bravo	Ford Focus	Ford Focus lowered	Ford Focus raised	Rover 75 standard
Subframe	Yes	No	No	No	No	Yes	Yes	No	No	No	No	Yes
Row 4	106	166	140	105	106	182	179	182	149	95	151	248
Row 3	80	175	133	123	150	127	142	100	65	151	35	116
Row 2	61	54	50	70	61	84	93	47	21	35	21	78
Row 1	36	26	36	29	30	20	15	23	19	21	0	13
Row (1+2)	83	79	86	97	91	100	108	69	40	56	21	80

	Rover 75 weak	Rover 75 strong	Renault Laguna	Mercedes E-Class	Honda CRV	VW Touareg	Volvo XC90	Nissan Micra 2	Renault Twingo	FIAT 500	Citroen C3 lower	Citroen C3 raised	Renault Koleos
Subframe	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	No	Yes
Row 4	255	301	172	171	235	320	295	98	77	146	113	142	192
Row 3	84	88	117	154	179	133	85	134	153	139	137	62	151
Row 2	94	70	74	68	64	20	30	58	107	123	61	29	101
Row 1	13	11	15	25	5	15	0	31	67	45	18	45	31
Row (1+2)	103	76	81	93	69	31	30	88	170	158	79	74	112

Figure 4.3: FWDB tests – Row load forces in kN up to 40 ms Note: Row (1+2) load calculated by adding Row 1 and Row 2 loads at each time step and then determining max load up to 40 ms.

The advantage of the modified metric can be seen by comparing how easily the Small Family Car 1 car meets the metric modifies performance limits (Table 5). It should be noted that the Small Family Car 1 has a quite high Primary Energy Absorbing Structure (PEAS) but also has a Secondary Energy Absorbing Structure (SEAS) subframe loadpath and was proofed to perform well in aligned and misaligned car-to-SUV tests.

Table 5: Comparison of Small Family Car 1 Row load forces with original and modified metric performance limits.

Row	Force Value KN	Original Metric Performance Limits kN	Modified Metric Performance Limits kN
F4	188	100 (109)	100 (109)
F3	107	100 (109)	85 (94)
F4+F3	295	N/A	200 (217)
F2	85	N/A	N/A
Total	543		

It is seen that with the modified metric the load requirement for Row 3 is reduced which enables the Small Family Car 1 to meet the metric requirements more easily than for the original metric. Indeed, if the original metric was implemented a manufacturer may have considered the Small Family Car 1 design inadequate and altered it because it was too close to the limit. This would not be the case for the modified metric.

It is recommended that further validation of the suggested values for the performance limits is undertaken to ensure that this metric is appropriate for regulatory application, in particular if a test speed of 50 km/h is chosen because the performance limits suggested above were formulated based on the available test data which had a test speed of 56 km/h.

4.2 Definition of Test Severity / Velocity

It was important to establish a test severity for the full width test procedures to ensure the candidate procedures were representative of the real world conditions. The existing UN-ECE Regulation 94 was used as a benchmark for the offset tests. A similar European benchmark was not available for the full width test and therefore a justification for test severities was developed in the project.

A review of reconstructed German accidents in the GIDAS database was developed by BASt and is presented in Figure 4.4. In principle the analysis combines the injury risks resulting from accidents with certain velocities with the accident risks at these velocities. The vertical axis is labelled “accumulated risk” but may also be referred to as “accumulated incidence” or “incidence” and represents the proportion of injuries reported over a range of delta-vs. Each point on the line is the average value for a moving window of 10 km/h to identify the potential contribution of a test delta-v related to real world crashes that occur within the window +/- 5 km/h for each reference delta-v. This conservative approach assumes that the test severity only influences vehicle designs and resulting occupant safety for crashes within this severity window. The example illustrates the peak incidence of MAIS 2+ injuries at 52 km/h and the speed range over which the risks are summed (47 to 57 km/h). All curves (MAIS 2, 2+, and 3+) exhibit peaks for delta-v around 52 km/h and fall off sharply after delta-v 55 km/h. This is not unexpected as the majority of collision cases occur for impact speeds below 50 km/h.

The real work data indicates that the highest risks for MAIS2+ injuries are in the range 47 to 57 km/h and that this impact severity should be used to direct future car designs. Given that a full width test delta-v usually involves a rebound velocity of approximately 10% the impact speed, a test speed of 50 km/h was selected for a full width test severity, regardless of the barrier face selected.

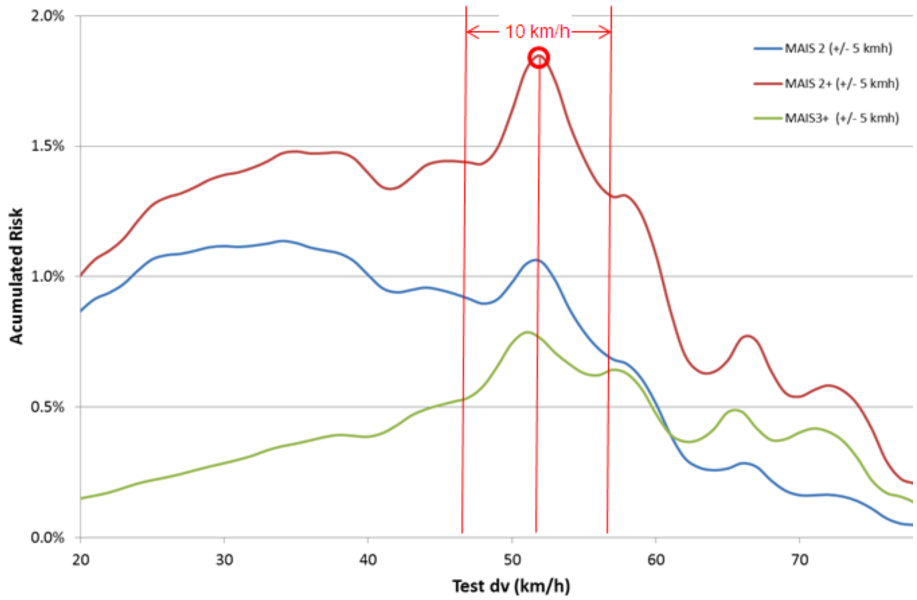


Figure 4.4: Incidence of injuries in high overlap accidents (overlap > 75 %).

4.3 Vertical Load Spreading

Structural interaction was a high priority work item in FIMCAR. The groups identified sub elements of such as structural alignment, horizontal load spreading and vertical load spreading. The latter is a particularly important issue to investigate as benefits of lower load paths and SEAS have been identified in earlier projects and international activities relating to higher vehicles, like SUVs, need to be addressed. To further investigate vertical load spreading, three specific tasks were identified:

1) Report on recent international research related to evaluation and performance of lower load paths and SEAS, specifically how far forward must a structure be positioned so that it can interact with a collision partner
2) Identify what characterises “appropriate” SEAS which provides a benefit in a car-to-car crash
3) Identify potential methods to assess or identify an appropriate SEAS

The benefits of vertical load spreading were identified in the VC-Compat project and confirmed in the FIMCAR car-to-car tests. Details of these tests are presented in the following sections.

4.3.1 Recent International Research

The most significant issue that was discussed during the development of a FW test was the issue of detecting structures behind the bumper cross beam that may not be directly loading a load cell wall early in the impact. Both Japan and the US were reviewing the loading patterns of vehicles on a FWRB to develop compatibility metrics for their full width legislated test. Japan had proposed that the structure of the vehicle should be evaluated before the engine begins loading the LCW. This approach was used in FIMCAR to develop of the FWRB metric (Reported in FIMCAR D3.1Adolph et al. 2012). This limited the evaluation of vehicle structures to the very forward structures and any forward mounted subframe or block beam could not be assessed before motor-LCW contact. The proposal of the Auto Alliance for an Over Ride Barrier (ORB) was made as one method to assess the SEAS of vehicles that are not otherwise detected in a FWRB. The test apparatus is shown in Figure 4.5 and details of the test procedure can be found in the paper of [{Patel 2009 #20}].

Figure 4.5: Example of ORB test configuration [{Patel 2009 #20}].

The importance of the vertical load distribution and its evaluation in a full width test was a critical issue in the WP3 activities in FIMCAR. Concerns were made about the potential to introduce a regulation that would legislate a vehicle type from the market. Vehicles with higher structures, like off road vehicles, could have difficulty meeting a requirement for applying loads into a certain vertical region on the FW barrier. It is undesirable to create a legal requirement that cannot be met by vehicles because they cannot be constructed to meet other requirements without the prove that not meeting the crash test criteria will necessarily result in unsafe cars. Thus the FWRB was seen to need supplemental test information.

The FWDB barrier was part of the WP3 activities and its proponents have claimed that it may be possible to identify lower load paths. JAMA provided test data of a vehicle which has SEAS located 378 mm behind the bumper cover and PEAS that is positioned within the Part 581 zone (Figure 4.6). Although the vehicle met the FWDB metrics, JAMA concluded that the FWDB was not able to measure the loads in the SEAS due to the weak crush strength of the first layer and the SEAS was not able to penetrate into the second, stiffer, layer.

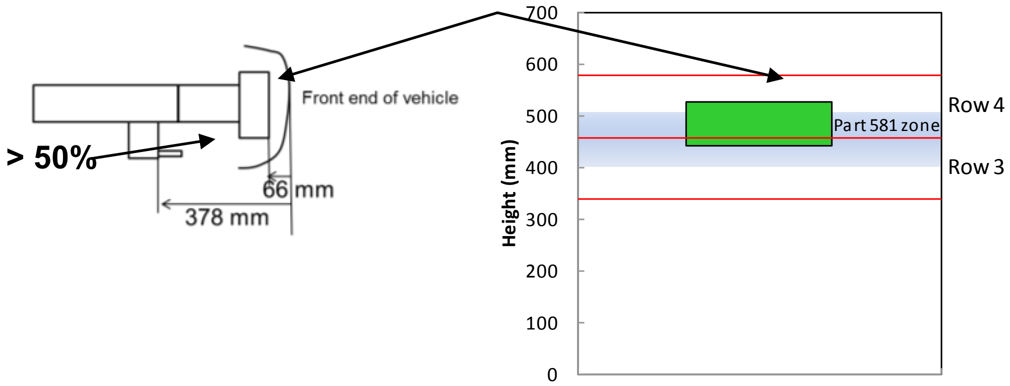


Figure 4.6: Test vehicle geometry of JAMA test.

The issues and activities described above were concerns within the FIMCAR consortium and further investigations of the SEAS and PEAS requirements for higher vehicles were conducted.

4.3.2 Accident Analyses

The real world performance of vehicles with taller structures has been part of many NHTSA projects due to the high proportion of LTV and SUV vehicles in the vehicle fleet. The Average Height of Force (AHOF) metric was developed as a potential compatibility metric to assess compatibility an update of the AHOF investigations is found in Summers et Prasad 2005. This metric has not found international acceptance and has a drawback for assessing lower structures as it assesses the entire loading profile as one force application position and does not treat the front structures separately.

The Alliance of Automotive manufacturers [Auto Alliance 2009] presented a self commitment to LTV and SUV geometry that would be implemented by 2009. Different studies have tracked the performance of vehicles to identify the benefits of the geometric requirements. The two most recent studies were conducted by IIHS [Teoh 2011] and NHTSA [Greenwall 2012]. The studies investigated the fatality risk for passengers of passenger cars struck by LTVs. In both cases the studies showed that late model LTVs that fulfilled the self commitment were performing better than corresponding model vehicles built prior to the commitment. Thus the geometric alignment of PEAS and SEAS with the part 581 zone has had benefits to traffic safety. The more crucial question is the identification of the effectiveness of the type of vehicle designs. Stage 1 vehicles comply by having a significant portion of their PEAS in line with part 581 and thus the main structures of both collision partners are in line. Stage 2 vehicles comply by positioning a lower structure under the PEAS to align in the Part 581 zone. This second option is specified in geometric requirements but has been more difficult to specify in a performance based test. The ORB [Patel 2009] is one proposed method to assess the performance of SEAS.

While both NHTSA and IIHS have identified benefits for passenger car occupants by the introduction of the geometrical alignment of structures, NHTSA has done a more thorough investigation of the different models and method (Stage 1 or Stage 2) of compliance [Greenwall 2012]. Table 6 shows the results from the NHTSA study divided by vehicle type and method of compliance.

Table 6: Effectiveness of vehicles complying to Auto Alliance Self Commitment.

	Number of reviewed models by method of compliance		
Vehicle Type	**PEAS (Stage 1)**	**SEAS (Stage 2)**	**Effectiveness**
Pickup Trucks	0	32	-4.9%
SUVs	24	15	17.5%

Communication with NHTSA indicated that the material did not allow for a separate analysis of Stage 1 or Stage 2 vehicles. It is relevant to point out that the vehicle type most dependent on Stage 2 approval (pickups) has not shown any benefit by complying to the geometric guidelines. Conversely, SUV type vehicles which predominantly have a Stage 1 approach to compliance have shown to be better than their predecessors. NHTSA points out that the benefits to car occupants is not solely due to the compliance of LTVs and SUVs to the self commitment as passenger car self protection has improved over the years and this also contributes to the reduced fatality rates. It is also important to consider that pickups are predominantly body-on-frame structures that are different from uni-body designs found on most SUVs.

The results of the accident analyses indicate that there are benefits to alignment of structures but the role of a SEAS or lower load path set behind the bumper is still not well understood. A test method to identify SEAS that is shown to be effective in car-to-car crashes is a central issue for the full width test to be proposed by FIMCAR.

4.3.3 Crash Tests and Simulation Analyses

The need of a second stage assessment and the appropriate method for evaluating was investigated by a review of previous test and simulation activities as well as new FIMCAR test and simulation results.

The ORB was proposed by industry to complement the full width test and has been evaluated by NHTSA. Patel et al. [Patel 2009] demonstrated with crash tests that vehicles fulfilling the ORB did not necessarily provide benefits in a car-to-car crash. The main reasons that can be identified:

1) The acceptance criteria are too generous. The requirement to meet a force threshold in the first 400 mm of travel can result in significant interaction of a stiff PEAS before any contribution of a SEAS with the collision partner.
2) The force measurement in a rigid load measurement system can overestimate the contribution of structures when a displacement based procedure is used.
3) The test method has no requirement for energy absorption of the structures and thus no demands are placed on the SEAS to maintain the threshold force.

An example of a vehicle with acceptable ORB performance is the GMC Silverado analysed by Patel et al [Patel 2009] and the structure is shown in Figure 4.7. The SEAS are small brackets hanging from the PEAS and fulfil the geometric requirements in the self commitment.

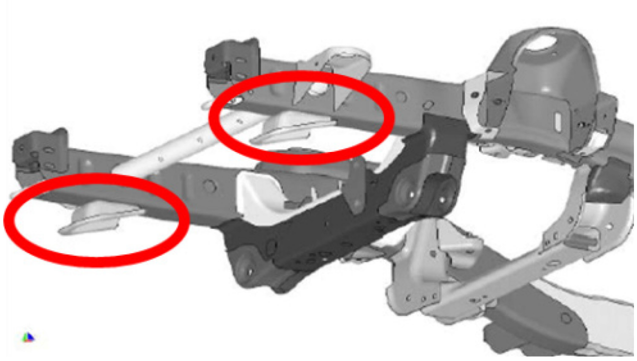


Figure 4.7: Silverado with SEAS structures.

The SEAS on the Silverado was sheared off in the ORB test but met the force requirements during the test period required. Figure 4.8 shows the test data recorded (left) and the vehicle undercarriage with the location of the SEAS bracket after the test (right).

Vehicle-to-vehicle simulations were used to assess the performance of the Silverado with and without its SEAS structure and the results showed negligible contributions of the SEAS configuration installed on the Silverado [{Patel 2009 #20}]. Although the study showed that the ORB also produced positive results for SEAS that made a contribution in a vehicle-to-vehicle crash, the false negative produced by the ORB was a point for concern.

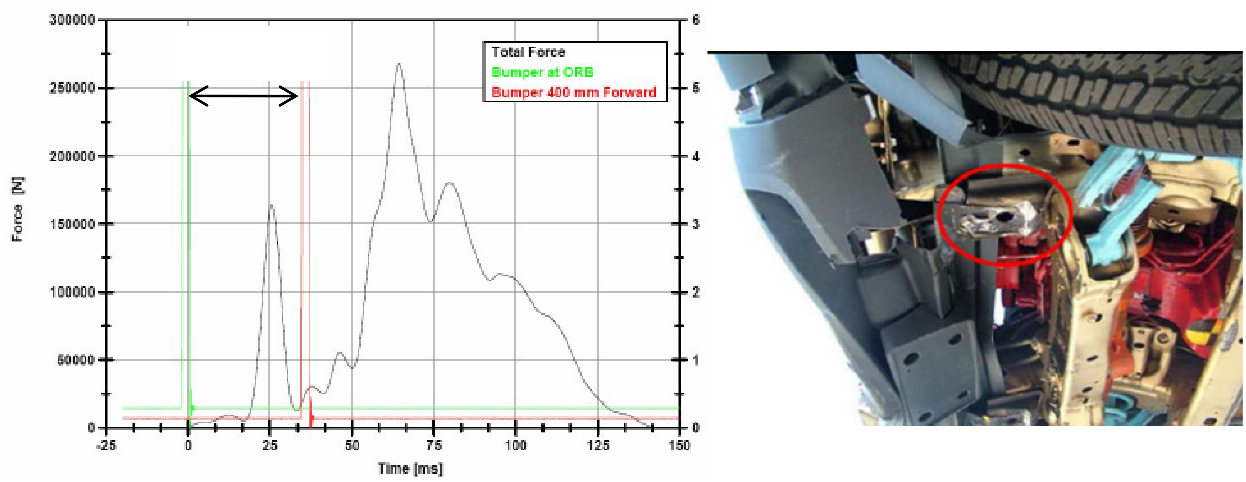


Figure 4.8: Silverado SEAS response in ORB test [Patel 2009].

Since the ORB has been designed predominantly for the large LTVs and SUVs in the US market, further simulations were conducted in FIMCAR to identify the suitability of the ORB for passenger car applications as well as the ability of the FWDB to detect SEAS. Car-to-car simulations were also explored to understand the ability of different sub-frame combinations to contribute to crash performance.

4.3.3.1 **FIMCAR Simulations with PCM Models**

Vertical load spreading and effective SEAS/lower load path structures were the focus of a FIMCAR WP6 request to WP5 to conduct computer simulations. The Parametric Car Models developed by TUB [Stein 2013/2] were used to investigate different car designs as shown in Figure 4.9. The subframe set back distance was positioned in 6 different positions (200 – 400 mm behind the bumper) to determine when the subframe is detected by the ORB. The models were then impacted against reference PCM models to identify the influence of the different subframe designs. The models were also simulated with impacts into the FWDB barrier to assess if the different subframe configurations were detected by the metric.

The PCM models were able to satisfy the ORB tests except for the case when the subframe was 400 mm behind the bumper. This was expected as the subframe must contact the ORB and deform before it can exert the 100 kN required. See Figure 4.10 where a successful test requires the curve to pass through the shaded area.

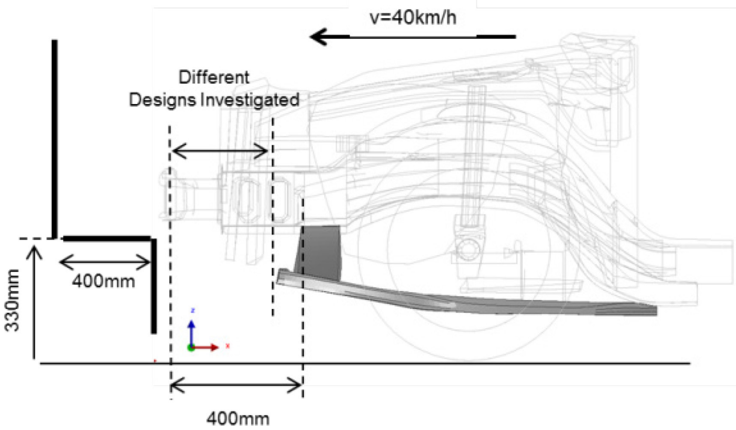


Figure 4.9: PCM model configuration with ORB.

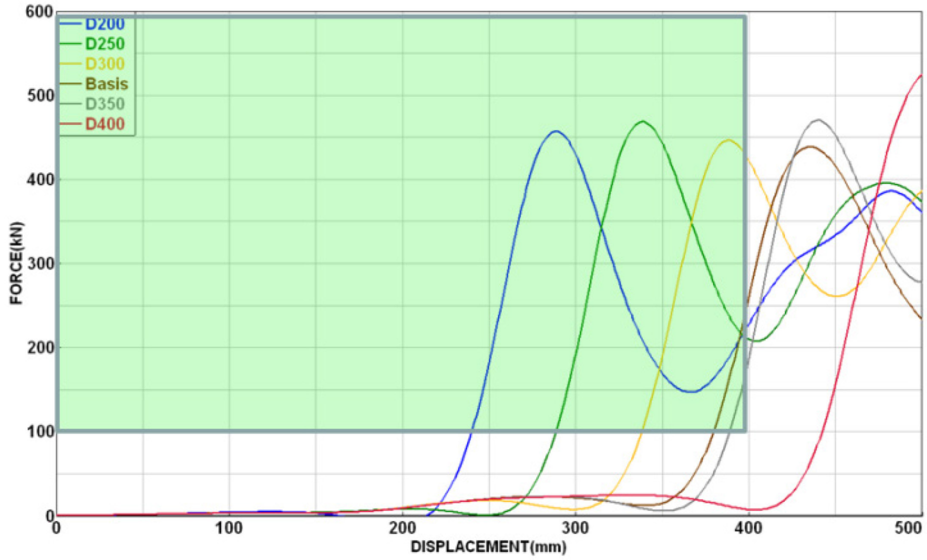


Figure 4.10: Force / PEAS displacement recorded for PCM models for ORB.

For the FWDB simulations, the vehicle was shifted vertically so that it would resemble a higher LTV or SUV (Figure 4.11, left). In all cases the lower load path was unable to create sufficient loads on the LCW so that the FWDB metric would be met. The row loads shown in Figure 4.11 show how little force is applied in Row 3.

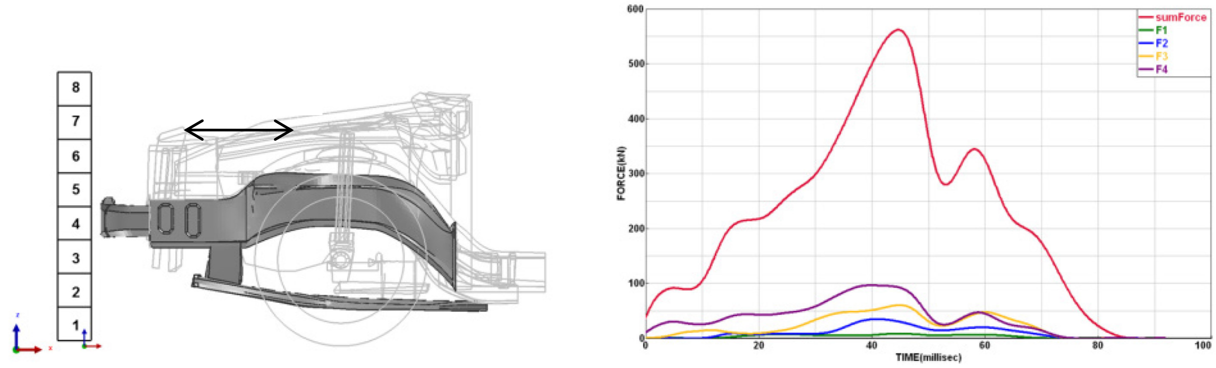


Figure 4.11: FWDB simulation configuration and sample results.

In a second series of simulations, the vehicle structure was adjusted so that the vertical connection between the PEAS and SEAS was moved forward (Option 1) and the subframe cross beam section height was also increased (Option 2) to create a larger contact surface on the deformable barrier (Figure 4.12). Even after the adjustments, the vehicle was not able to meet the FWDB criteria although there were improvements in the loads recorded on the LCW. Figure 4.13 shows the LCW results and there are noticeable improvements in Rows 2 & 3 (lower 2 curves) due to the subframe modification.

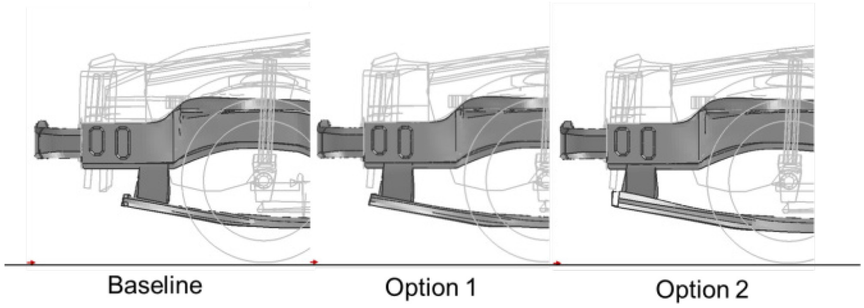


Figure 4.12: Subframes in second simulation series.

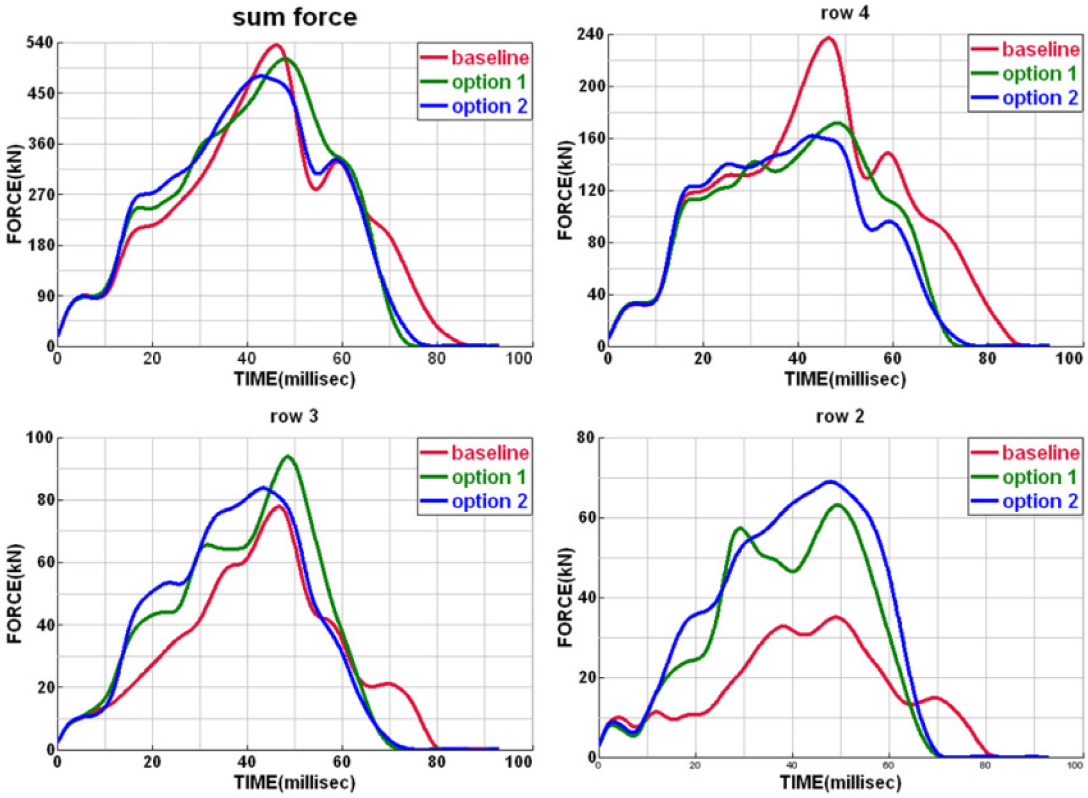


Figure 4.13: FWDB results in second series of PCM modifications.

The summary of the FWDB load cell loads processed for the proposed metric are presented in Table 7. In all cases the Row 3 loads are below 100 kN and the Row 2 loads never exceed the 70 kN needed to achieve a Limit Reduction in Row 3.

The PCM simulations for barrier impacts needed to be compared to simulations of the same vehicles impacting other vehicle models to evaluate the performance of the subframe configurations under car-car conditions. No occupants and restraint systems were modelled so only compartment intrusions and accelerations were used to compare the different simulations results. In all cases the PCMs with different subframes were positioned to be higher than the collision partner to evaluate the effectiveness of the lower load paths.

Table 7: Calculation of FWDB metric for PCM simulations in second simulation series.

Limit Reduction Metric			
	Misaligned (aligned row 4)	**Option 1** (subframe and vertical connection far forward)	**Option 2** (subframe cross section increased and vertical connection far forward)
F_{sum} [kN]	458	427	467
F_4 [kN]	190	146	155
F_3 [kN]	61	66	81
$F_3 + F_4$ [kN]	251	212	236
$0.4F_{sum\_@\_40ms}$ [kN]	183,2	170,8	186,8
$0.2F_{sum\_@\_40ms}$ [kN]	91,6	85,4	93,4
F_2 [kN]	32	46	63
LR [kN]	(-38 → 0)	(-24 → 0)	(-7 → 0)
	fail	fail	fail

The results of the first car-to-car series with the PCM investigated the reference PCM (a Large Family Car – LFC) impacts with a smaller Super Mini (SM) and a heavier Executive (Exe) car. When the intrusions were compared, no benefit for the different subframe designs could be observed. It was observed that the small section of the subframe cross beam and the rearward position of the vertical connection would allow a vertical fork effect to occur and reduce the interaction of the subframes with the partner vehicle's structures. When the second series (with better subframe designs) were analysed (see Table 7), there were improvements in the case of Option 2 compared to the baseline case (unmodified LFC against itself as shown in the lower part of the table).

Table 8: PCM car-to-car simulation results.

	Baseline	Modified car
Baseline - Misaligned	-125mm	-220mm
Baseline - Option 2	-98mm	-122mm
Reference	Baseline	Baseline
Baseline - Baseline	-163mm	-167mm

An earlier interaction of the vehicles could be observed in the acceleration vs. displacement plots presented in Figure 4.14. The red curves (with option 2) show earlier interactions than the standard vehicle accelerations (blue).

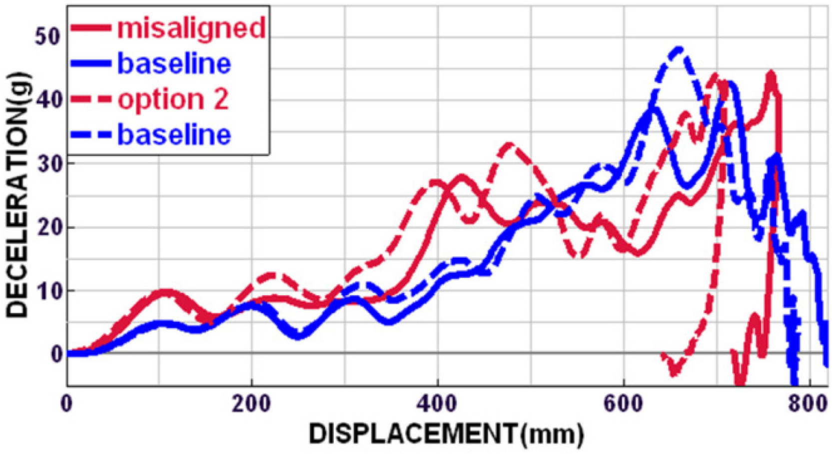


Figure 4.14: PCM simulations of reference case and best subframe configuration.

The PCM simulations should be reviewed as there is a significant simplification made when the vehicle structure was modified. Subframe geometry was modified only without balancing of the upper and lower load path stiffness's. The original PCM model was designed to have acceptable scores in the offset and full width test conditions but no optimisation of the baseline or modified vehicles were conducted. Better FWDB results would be expected in the modified cases if a more extensive engineering analysis was conducted.

As a result of the PCM simulations, the values for the Limit Reduction (LR) and allowable adjustment of Row 3 loads was reviewed. As seen in Table 7, the Row 3 loads were at 80 kN and Row 2 loads were nearing 70 kN. The limit reduction proposed earlier in this chapter was based on the test data that suggested that crash structures tended to produce more than 70 kN on a row. Given that the vertical fork effect was observed in the simulations and that 70 kN row loads were produced by vehicle structures that were giving positive results in car-to-car impacts, it was proposed that the limit reduction in Row 3 should not result in measured Row 3 loads being under 70 kN. These values are based on 56 km/h FWDB tests.

4.3.3.2 **Car-to-Car Simulations with other Vehicle Models**

Chalmers and VTI researchers had conducted an earlier study on the effect of subframe on car-to-car impacts [Park 2009, Thomson 2008]. These simulations indicated how modifications of the public FE model of a Ford Taurus affected the crash response. As part of WP6 request to WP5, the Taurus models were simulated in a FWDB impact by TUB so that the FWDB metrics could be correlated to the car-to-car crash performance. The subframe configurations investigated are shown in Figure 4.15.

The results of the car-to-car simulations were presented in [Park 2009, Thomson 2008] and are summarised in Table 9. What is significant to note is that the extended Subframe tended to improve the vehicle performance and the shortened Subframe tended to decrease the performance compared to the baseline vehicle. As seen in Figure 4.15, the basic subframe is more than 300 mm behind the bumper and the shortened Subframe is more than 400 mm.

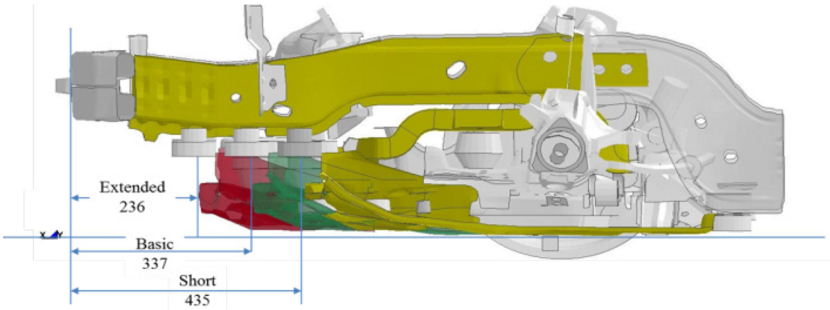


Figure 4.15: Variations of Ford Taurus subframe.

Table 9: Car-to-car of different Taurus subframes (O: Good, Δ: No better and X: Poor) [Thomson 2008].

	Cases		Difference¹ (mm) in		Vehicle ¹²		Compatibility Performance³
	Horizontal Overlap	Vertical Overlap	AHOF	AHOF400	Self Protection	Partner Protection	
B2E	100%	100%	-17	-64	Δ	O	O
	60%				X	O	X
	40%				X	O	X
	100%	25%	88	41	Δ	Δ	Δ
	60%				X	O	X
	40%				X	X	X
E2B	100%	25%	122	169	Δ	X	X
	60%				O	O	O
	40%				O	O	O
B2S	100%	100%	56	25	Δ	X	X
	60%				X	X	X
	40%				Δ	X	X
	100%	25%	161	130	O	X	X
	60%				X	Δ	X
	40%				O	X	X
S2B	100%	25%	49	80	Δ	O	O
	60%				X	O	X
	40%				Δ	Δ	Δ

1. Difference is given by subtracting AHOF or AHOF400 of vehicle 1 from one of vehicle 2.
2. Self- and partner-protection of vehicle 2 is opposite of vehicle 1.
3. The results are compared with B2B under same C2C test condition.

The simulations with the FWDB show that the shortest subframe has essentially no contact with the deformable barrier at the 40 ms reference time. Figure 4.16 shows that both the basic and extended subframes are well into the first layer while the short subframe (bottom) is just starting to contact the barrier.

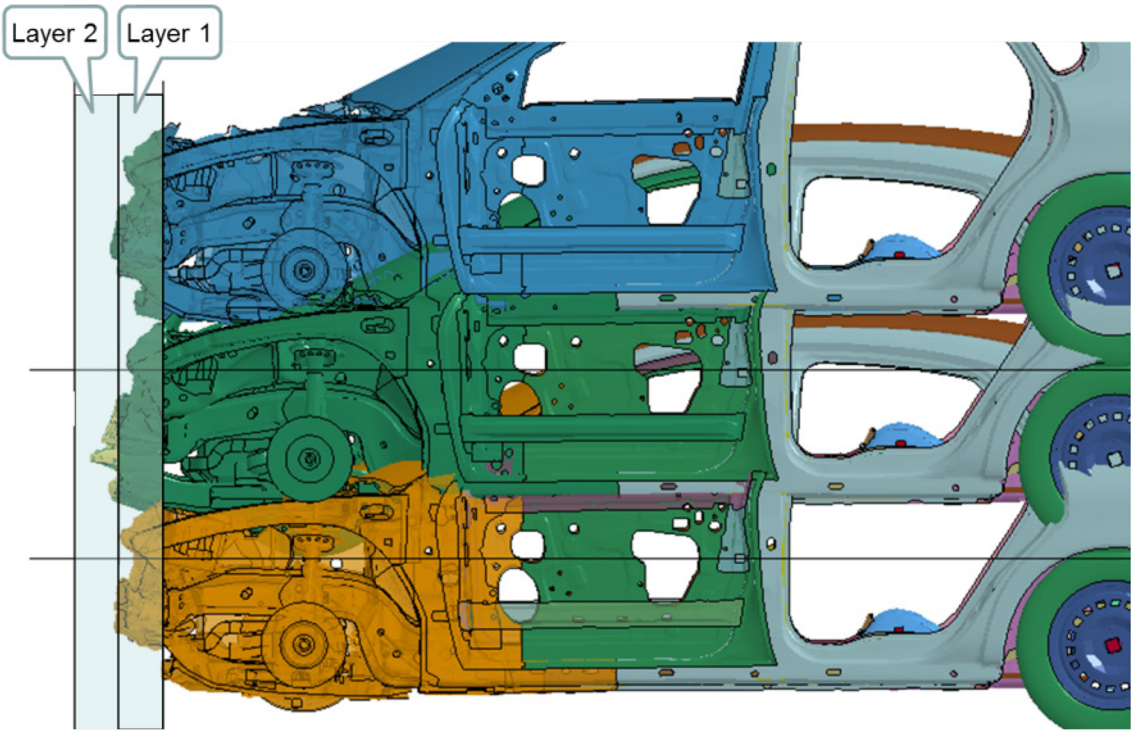


Figure 4.16: Vehicle/barrier reference dimensions at 40ms.

The FWDB tests were simulated with the Taurus in its raised conditions. The car-to-car simulations were conducted with the Taurus having a vertical offset of 25% - 25% of the vertical section height of the longitudinals were in contact. The row loads calculated for the cases are shown in Figure 4.17. All three cases meet the FWDB metric. It can be seen that the shortened subframe case just meets the 100 kN in Row 3. The raised Taurus still has some of its PEAS extending into Row 3 and this is enough to load this area of the barrier sufficiently for a positive evaluation. The Row 2 loads show significant differences for the different cases.

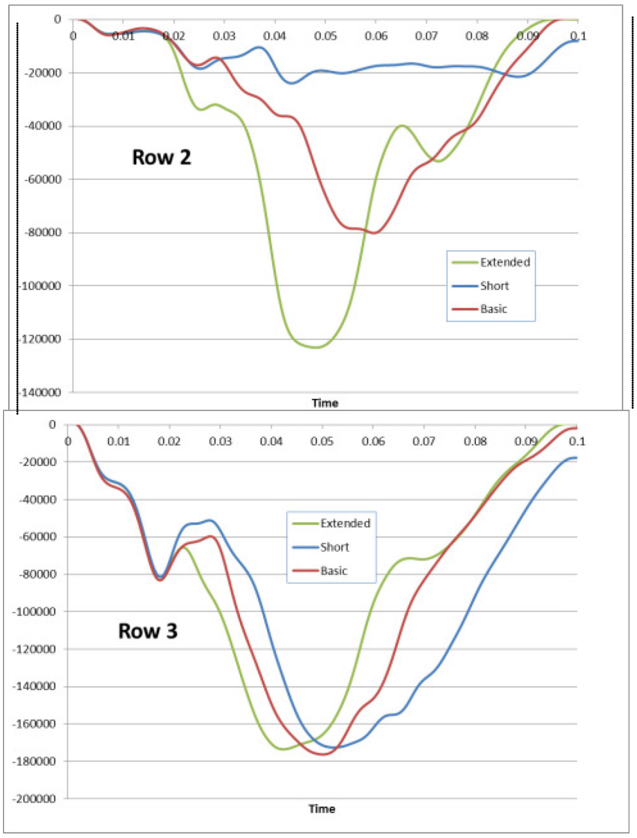


Figure 4.17: Row loads in FWDB tests with Taurus.

The results of the Taurus simulations showed that vehicles barely meeting the FWDB metric had poorer performance than those with higher loads in Row 3 and 4. The results also showed that vehicles producing Row 2 loads over 80 kN were better than those with only 40 kN. The barrier was starting to detect subframes 337 mm behind the bumper crossbeam and it was this region 300 to 400 mm that subframes could be seen to introduce differences in car-to-car crash performance.

4.3.3.3 **Other Test and Simulation Results in FIMCAR**

The influence of vertical load spreading can be inferred from the car-to-car test and simulation activities in WP6. FIMCAR Deliverable D6.1 [Sandqvist 2013] describes the results of different vehicle configurations. The results showed that the vehicles with lower load paths, i.e. better vertical load spreading, performed better than single load path vehicles. It was also shown that cases where SUV 1, in both its standard or lowered, ride height produced reasonable compatibility results in striking a smaller passenger car due to its well designed lower structures. Section III shows that the results tended to be better when the structures are aligned, but even the misaligned case could have acceptable structural interaction. This can be related to the ability of SUV 1 to produce acceptable FWDB results in its standard ride height.

A simulation and side impact study was conducted with a crossover SUV 3 and its sister vehicle in a sedan configuration. The SUV was fitted with a lower load path that could be removed for simulation and test purposed. The side impact tests are reported in Section III and showed that vertical load spreading was desirable for side impact configurations. The complementary frontal impact investigation of the SUV 3 had similar results as for SUV 1.

4.3.4 Summary for Vertical Load Spreading

The tests and simulations conducted in FIMCAR indicate that structural alignment is a high priority for frontal impact and compatibility and that vertical load spreading is an important supporting characteristic. In all cases, vehicles with vertical load spreading can be detected with the FWDB if the structures are less than 400 mm behind the bumper. Lower load paths that are detected in a FWDB by exerting more than 70 kN (in the 56 km/h test case) show a benefit for car-to-car crash performance. An FWDB metric that rewards vehicles with 70 kN in Rows 2&3 would be beneficial for vehicle safety.

4.4 Horizontal Load Spreading

4.4.1.1 Background

The FIMCAR project produced a list of assessment requirements and priorities which ranked load spreading as a top priority [Thomson 2013]. After the review of the candidate test procedures, the FIMCAR consortium decided to proceed with the combined FWDB and ODB tests as the best assessment approach based on the current state of the art [Thomson 2013]. Vertical load spreading is addressed in the FWDB metrics, but horizontal load spreading was not addressed in any of the final test procedures. The exclusion of the (M)PDB test in the matrix reduced the potential to assess horizontal load spreading, so FIMCAR investigated a Horizontal Load Spreading assessment using the FWDB test to increase benefit of the new test procedures

4.4.1.2 Review of Previous Work

Horizontal load spreading with the FWDB has been investigated in earlier projects and resulted in 3 different versions:

- **a)** Part of a global homogeneity metric “Column Homogeneity” (Hc) (beginning of VC-Compat)
- **b)** Separate “Horizontal Negative Deviation” metric (during VC-Compat)
- **c)** Horizontal Structural Interaction (HSI) metric (VC-Compat & Aprosys)

The common problems/concerns with a) and b) were that they are based on peak loads in each load cell which may occur at different times in the event and may not be physically realistic. The metrics did not show consistent results with a series of Rover 75 tests with modified bumper stiffness’s. The main issues for c) were poor repeatability observed in some APROSYS tests, no clear threshold for performance limits, and the assessment itself was seen as too complex.

4.4.1.3 FIMCAR Approach

A prerequisite for a horizontal load spreading metric is that the metric for an FWDB test should reflect car-to-car crash performance. The bumper beam characteristics of 3 different cars were defined based on car-to-car testing:

- VW Touareg: Stiff and narrow cross beam (Figure 4.18)
- VW Golf: Golf stiff crossbeam (Figure 4.19)
- Opel Astra: Weak crossbeam (Figure 4.20)

Figure 4.18: Front Structure of VW Touareg, left: VW Touareg versus Golf, right: VW Touareg vs. Opel Astra.

Figure 4.19: Front Structure of VW Golf, left: VW Golf versus Touareg, right: VW Golf vs. Volvo XC 90.

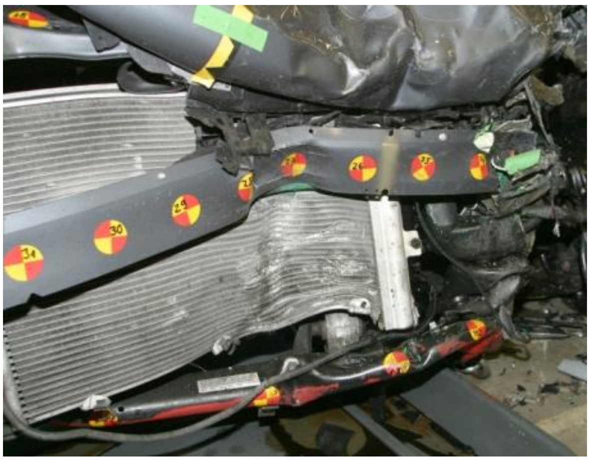


Figure 4.20 Front Structure of Opel Astra after crash test versus VW Touareg.

The bumper beam characteristics observed in car-to-car testing can also be confirmed by the footprint produced by the bumper beam in the barrier of the PDB 50% test (Figure 4.21).

Figure 4.21: PDB barriers after crash tests; Left: VW Touareg, Middle: VW Golf, Right: Opel Astra.

FWDB Testing

The results from the FWDB test of the above mentioned cars were analysed with respect to horizontal load spreading assessment. The analysis was done both by using the LCW visualization tool in the FIMCAR database and by looking at the peak forces for each column in Row 3 and 4 of the Load Cell Wall. Both analyses were done up to 40 ms (before the engine starts to load the barrier). As can be seen in Figure 4.22, the method to summarise the peak forces for each column in Row 3 and 4 does not at reflect all the result from the car-to-car testing. The VW Touareg appears to have a very weak cross beam relatively to the force from the longitudinal side members. Furthermore, the method does not seem to clearly distinguish the difference in bumper characteristics between VW Golf and Opel Astra, which, when reviewing Figure 4.22, look relatively similar even though they have different car-to-car performance.

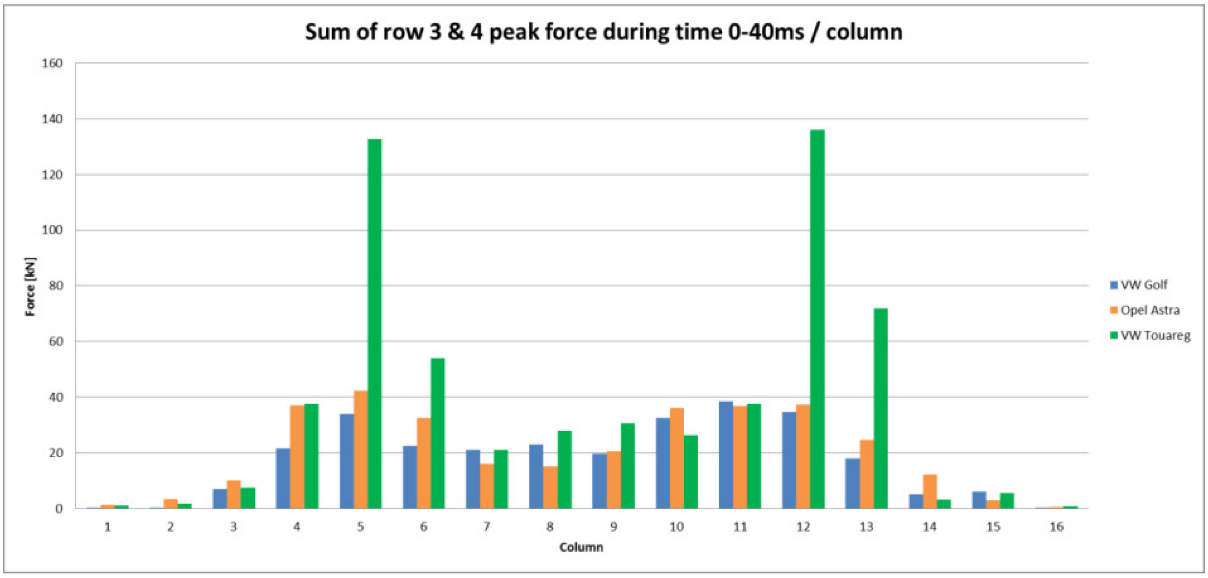


Figure 4.22: Sum of row 3 & 4 peak force during time 0-40ms / column.

By using the LCW visualization tool in the FIMCAR database, force distribution plots like Figure 4.23, Figure 4.24 and Figure 4.25 can be produced. For the VW Touareg (Figure 4.23) it is obvious that the car-to-car characteristics are not reflected in this plot and even looks more like the opposite case, the beam is very weak relative to the longitudinal side members. There is a possibility to distinguish between the bumper characteristics of the VW Golf and Opel Astra, but this approach does not discriminate between the cases as well as desired.

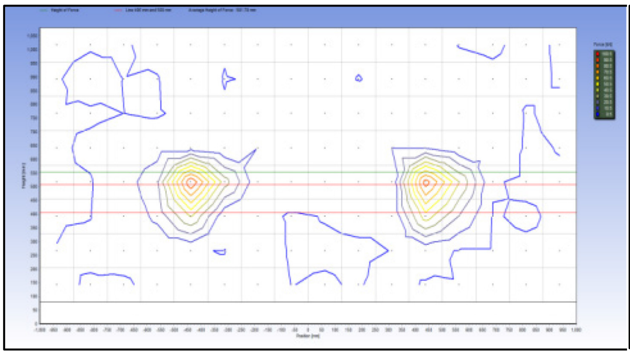


Figure 4.23: VW Touareg.

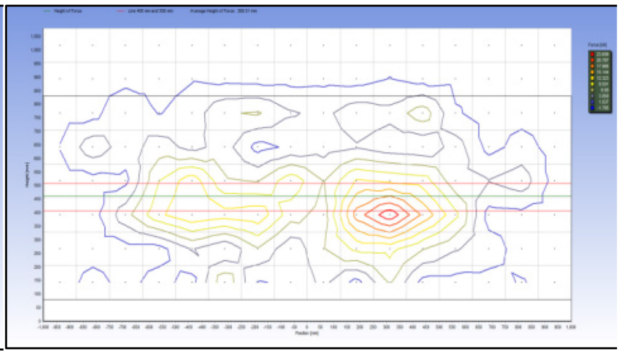


Figure 4.24: VW Golf.

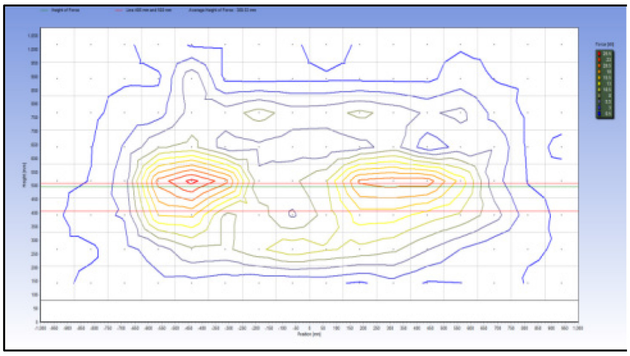


Figure 4.25: Opel Astra.

4.4.1.4 **Summary**

The FIMCAR approach to assess horizontal load spreading in the FWDB test started with two relatively simple methods to study the potential for a horizontal load spreading metric. These two methods clearly show that the potential is very low to comply with the prerequisite that the metric should reflect the characteristics proved in car-to-car testing. The results for the VW Touareg were, in particular, contradictory to what was observed in both car-to-car and PDB tests to such an extent that further attempts to develop a metric were considered pointless. It was decided to not attempt any further development of a horizontal load spreading metric for the FWDB within the FIMCAR project.

5 DEVELOPMENT OF LOAD CELL WALL CERTIFICATION AND CALIBRATION PROCEDURE

The use of an LCW for the assessment of cars requires a well defined and agreed LCW Certification procedure suitable for inclusion in regulation.

The proposed procedure was developed by Humanetics with support from other FIMCAR partners and Kistler (in this chapter referred to partners). This report presents the activities done and resulting documents.

5.1 Approach and Reference to Contents in the Report

Possible approaches for the certification of assembled walls were discussed with FIMCAR partners. Using the expertise from partner's options like wall flatness measurements, dynamic impact test using trolley with well defined impact area, load cell static calibration and load cell dynamic calibration were evaluated. Regarding the certification of installed walls it was decided to only have requirements on wall flatness included. Other options like full scale trolley tests with well defined loading surfaces are too expensive and include inaccuracies like orthogonality to the wall. In addition to the wall certification the need of a load cell specification and calibration section in the protocol was forwarded by the partners. Here options of static and dynamic calibration were discussed. As currently no proven methods exist for calibration under dynamic loading conditions it was decided to stick to static methods. Static calibration is also applied in load cell calibrations used in other tools used in the crash safety assessment of cars like Anthropomorphic Test Devices (ATD's).

5.1.1 Static Calibration of Load Cells

Static calibration is currently done for all LCW's in Europe using specifications as set by the LCW manufacturers. However, for usage in test protocols load cell specifications and performance limits are needed. Also a calibration procedure is required that includes information on items like hysteresis and non-linearity. In discussions with partners it was decided to generate a Load Cell Specification and Calibration document based on the following documents:

- SAE J2570: Performance Specifications for Anthropomorphic Test Device Transducers [SAE 2001]
- ISO 6487: Measurement techniques in impact tests – Instrumentation [ISO 2012]
- SAE J211: Instrumentation for Impact Test, Rev. 07/2007 [SAE 2007]
- DIN EN ISO 376 [DIN 2011]

Using the references mentioned above specifications and a calibration protocol were defined for the load cells. Parameter values were set based on needs for the FIMCAR metrics and manufacturers specifications of existing walls. The protocol is included in Annex A of this document.

After establishing a draft version of the protocol it was applied to a series of load cells from FIMCAR partners. Calibrations were performed to check and refine values for parameters like hysteresis and non linearity. Chapter 5.3 of this report describes the load cell calibrations done and the resulting parameter values. Final values are included in the protocol of Annex A.

5.1.2 Load Cell Wall Flatness

The wall flatness is mainly (or even only) an issue in case a barrier with deformable element is used in front of the LCW. The barrier is backed by a plate of about 2 mm thickness which spreads the loads between cells which are not aligned. Although non-alignment of cell faces can (at least partially) be compensated by adjusting the protective layers it was decided to collect flatness data from a number of existing walls and based on this define requirements for this parameter.

To define requirements for the wall flatness measurements were done on three different LCW's. Cell locations in 3-D space were measured using FARO arms. Data were then processed to reveal information on flatness of existing walls. For one of the walls the flatness information was compared against results from trolley tests with a flat impacting surface. Peak loads and loading histories were correlated with cell positions in depth direction. Results of the wall flatness analysis are included in chapter 5.4.

The resulting values for the wall flatness were used to define a LCW certification procedure as included in Annex B. Other requirements like cell size, ground clearance, cell numbering are straightforward and did not need any further investigations.

5.2 Static Load Cell Testing

To confirm parameters proposed for the Specification and Calibration document load cells available from FIMCAR partners were calibrated according to the procedures and output generated for sensitivity, non linearity and hysteresis. This chapter describes the test set-up, analysis methods and test results.

5.2.1 Test Set-Up

The load cell tests were performed on a calibrated INSTRON machine shown in Figure 5.1.

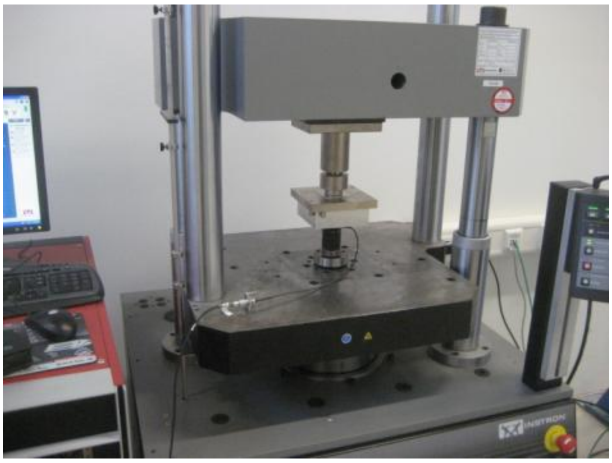


Figure 5.1: Load cell test in INSTRON machine.

The following loading sequence was applied to each cell (see Figure 5.2):

1. Three preloads up to 200 kN
2. Loading up to 200 kN increasing the load from 0 to maximum value in five steps. After each step some time to achieve stable equilibrium of the applied load level was considered. In the sequel this loading type is referred to as stable load condition.
3. Loading up to 200 kN with a continuous dynamic loop directly followed by unloading. This loading type is referred to as dynamic loop condition.

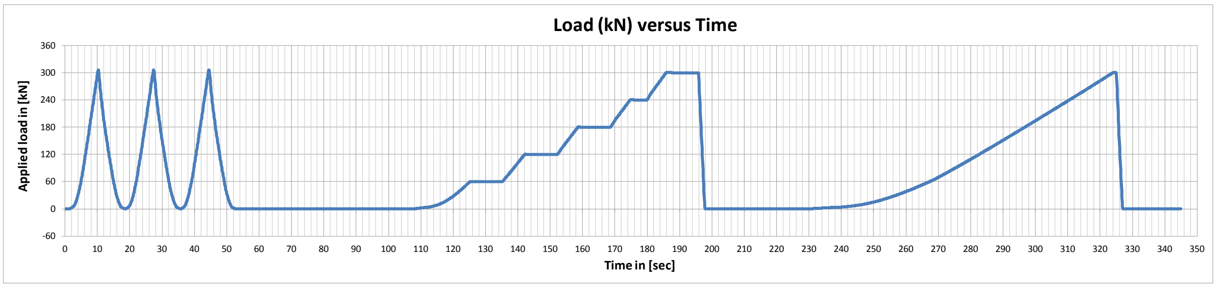


Figure 5.2: General loading sequence.

A total number of 10 load cells were subjected to the loading described above. The cells were provided by FIMCAR partners IDIADA (1 cell), BASt (2 cells), TRL (5 cells). In addition Kyowa provided 3 cells. One of the TRL cells was tested with and without protective layer.

5.2.2 Data Analysis

Through the analysis of the test data information can be obtained on the sensitivity, the non-linearity and the hysteresis. See Figure 5.3 for the definitions of these parameters. In the next sections these analyses are explained in more detail.

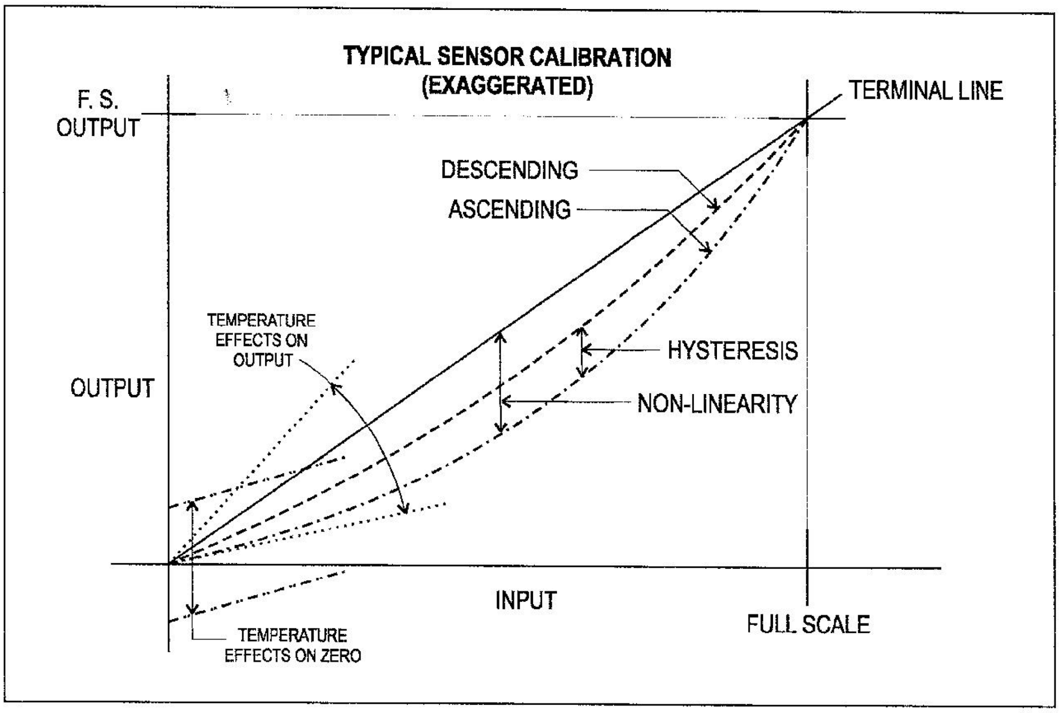


Figure 5.3: Analysis definitions according SAE J2570 standard.

5.2.2.1 **Load Cell Sensitivity**

The load cell sensitivity is defined as the output in mV/V at maximum load (full scale load level). This can be established from the stable load and the dynamic loop conditions. Hysteresis effects may cause that the sensitivity value is slight lower for the stable loop condition.

Stable load condition

At the maximum load level (step five in the stable load application) the average applied load and average load cell signal is calculated over two seconds of stable load (~20 samples). The output at maximum load level is calculated assuming a linear relation between load and output. See for example time window from 192 to 194 seconds in Figure 5.4 below:

- The measured average applied load is 299.998854 kN
- Average load cell output -1.356250 mV/V
- Resulting sensitivity at maximum load (300 kN) = 300 / 299.998854 * -1.356250 = -1.356255 mV/300 kN/V.

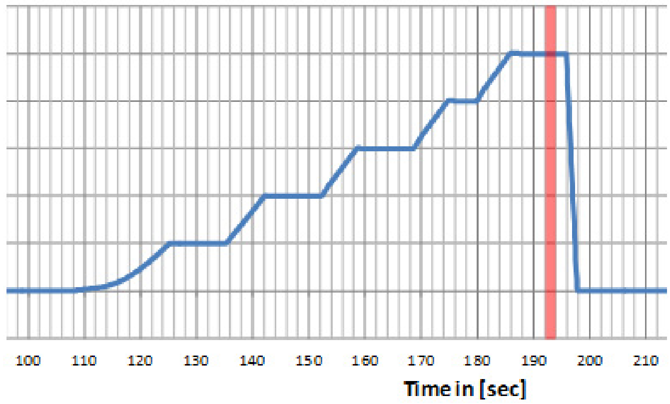


Figure 5.4: Time window of 2 seconds at full scale load level.

Dynamic loop condition

In this loading condition two data points close to the full scale load level in the loading curve of the continuous dynamic loop are taken and extrapolated to the full scale load level. See for example Figure 5.5:

- Data point 1: Applied load 297.159183 kN, Measured output -1.346150 mV/V
- Data point 2: Applied load 299.474072 kN, Measured output -1.356280 mV/V
- Sensitivity at 100 % Full Scale load level (300 kN) is -1.358581 mV/300 kN/V (extrapolated)

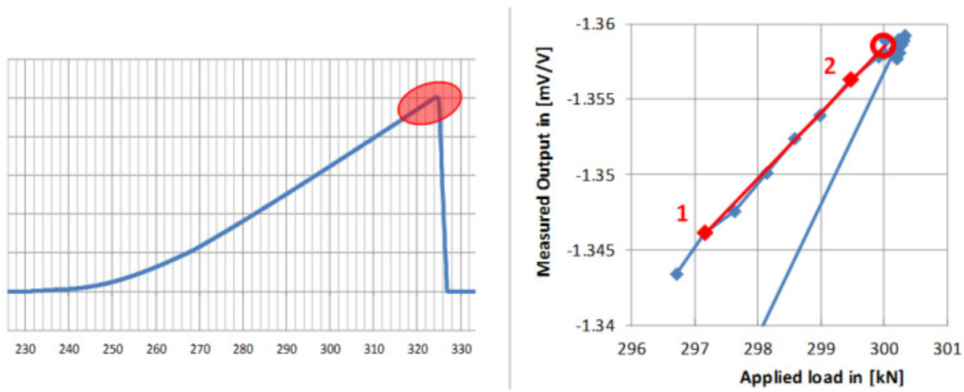


Figure 5.5: Extrapolation of measured data close to the full scale load level in the dynamic loop.

5.2.2.2 **Non Linearity**

The load cell non linearity as depicted in Figure 5.3 can be established in the stable load and the dynamic loop conditions. Also for this parameter hysteresis effects may introduce small differences between both loading conditions. For the non linearity the deviations of the output at 0%, 20%, 40%, 60% and 80% full scale load level is established with respect to a straight line (the so called “Terminal line”) through zero load zero output and the output at maximum load level.

Stable load condition

a. At 0%, 20%, 40%, 60%, 80% and 100% full scale load level the average applied load and average load cell signal is calculated over two seconds of stable load (about 20 samples) (see Figure 5.6).
b. These average stable load output results are scaled to the nominal values using the two adjacent average results.
c. The terminal line is the line through zero load zero output and the output at full scale load level (sensitivity)
d. At each load level is the deviation of the average stable load output results at nominal load with respect to the terminal line divided by the output at full scale load level is calculated.
e. The non linearity is the maximum deviation from the terminal line divided by output at full scale load level

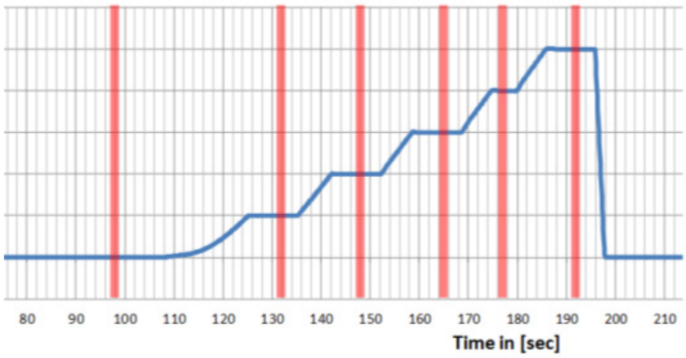


Figure 5.6: Time windows of 2 seconds at zero and 20%, 40%, 60%, 80%and 100% full scale load level.

Dynamic loop condition

See (Figure 5.7):

a. The terminal line is the line through zero load zero output and the output at full scale load level (sensitivity)
b. At each data point the deviation of the output results with respect to the terminal line divided by the output at full scale load level is calculated.
c. To stabilize the deviation the average over 40 samples is calculated
d. At 0%, 20%, 40%, 60%, 80% and 100% full scale load level the deviation is read from the averaged deviation.
e. The non linearity is the maximum deviation from the terminal line divided by output at full scale load level determined at 0%, 20%, 40%, 60%, 80% and 100% full scale load level

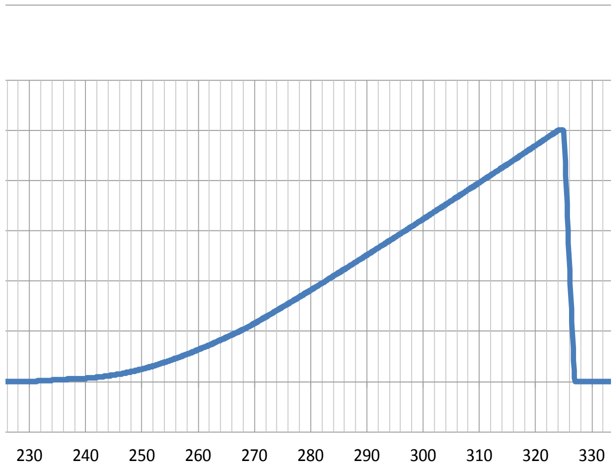


Figure 5.7: Dynamic loop signal.

5.2.2.3 **Hysteresis**

For the hysteresis the deviations of the output at 0%, 20%, 40%, 60% and 80% full scale load level between the loading and the unloading curve is established as depicted in Figure 5.3. The deviation is expressed in percentages of the output at maximum load level. This is analysis in the dynamic loop test conditions (see Figure 5.8).

a. All data points on the loading and the unloading curve are selected separately.
b. Fourth order polynomial trend line approximations of the data point on the loading and unloading curve are made separately.
c. At 0%, 20%, 40%, 60% and 80% full scale load level the deviation between both polynomial lines as calculated and divided by output at full scale load level.
d. The hysteresis is the maximum deviation between loading line and unloading polynominal approximation divided by output at full scale load level

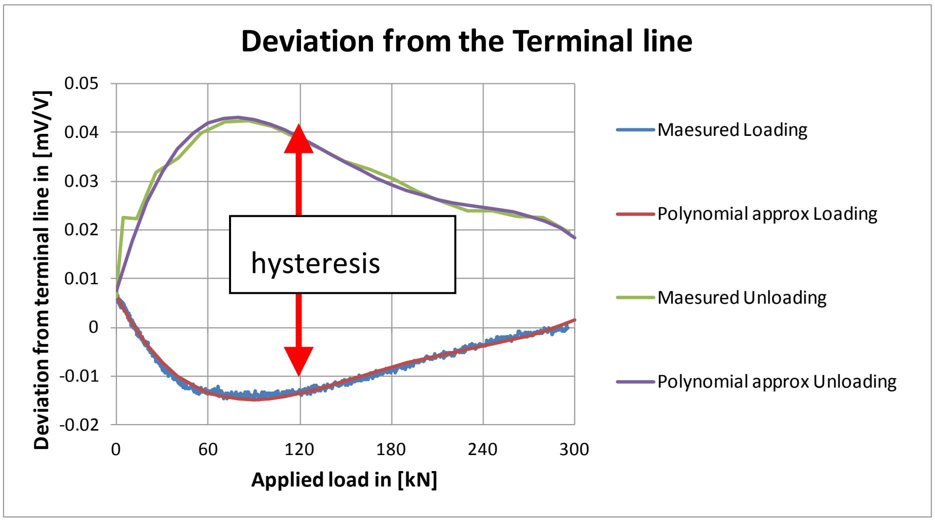


Figure 5.8: Deviation from terminal line of loading and unloading curve Measured and polynomial approximation.

5.2.3 Results

Table 10 below shows results for all load cells tested. It can be seen that the non linearity achieved over these cells is generally less than 1% as previously proposed. This value is therefore considered as achievable and included. The hysteresis however appears to be larger than the originally proposed 1%. Except for the BASt cells (in house manufactured cells) most load cells seem to be capable of reaching a hysteresis of 2%. This value is adopted in the protocol of Annex A.

Note that tests on two cells from the TRL wall were repeated. Cell unit number 912042 showed a high hysteresis value in the first test. To confirm this result test were repeated confirming the outcome. As further check the test on cell unit number 912091 was repeated to see if repeated measurements show different results. Again identical results as for the first test were found.

Finally one of the cells from TRL was tested with protective wooden layer. In this test local denting of the layer did occur directly underneath the stamp. It concerns localised deformation occurring due to the high differences in stiffness of the wooden layer and the cell itself. It is therefore recommended not to test cells including the wooden layer.

Due to the fact that no fixtures were available for cross talk and offset loading testing on the BASt and Kyowa cells these parameters were not investigated in the current study. Calibration data from load cells available from Humanetics indicate that values of about 1% are reached (both for transverse and vertical loadings). On this basis the cross talk value was set at 3% for the time being. Other parameters related to offset loading and free air resonance are to be set in future studies as indicated in Annex A.

Table 10 Sensitivity, non linearity and hysteresis of load cells tested in FIMCAR

Load Cell			**Stable load method**			**Dynamic loop method**			**Hysteresis**
									Dynamic
		Full Scale	Sensitivity		NonLinearity	Sensitivity		NonLinearity	Hysteresis
	unit	kN	mV/V @FS	mV/V/kN	max in %FS	mV/V @FS	mV/V/kN	max in %FS	max in %FS
	Draft requirement				< 1.0%			< 1.0%	< 1.0%
Kyowa	398390137	300	0.850537	0.002835	0.79	0.850848	0.002836	0.78	1.81
Kyowa	398390140	300	0.853035	0.002843	0.80	0.853620	0.002845	0.74	1.65
Kyowa	398390141	300	0.853811	0.002846	0.75	0.855314	0.002851	0.68	1.74
IDIADA	0216618	300	0.706995	0.002357	0.92	0.707790	0.002359	0.72	1.69
TRL	912009	300	-1.378615	-0.004595	0.55	-1.380067	-0.004600	0.24	1.78
TRL	912042 NW	300	*-1.356255*	*-0.004521*	*1.30*	*-1.358581*	*-0.004529*	*0.97*	*4.07*
TRL	912042 NW (2)	300	*-1.355427*	*-0.004518*	*1.36*	*-1.358709*	*-0.004529*	*1.04*	*4.19*
TRL	912091	300	-1.372614	-0.004575	0.54	-1.373373	-0.004578	0.26	1.90
TRL	912091 (2)	300	-1.368753	-0.004563	0.51	-1.368557	-0.004562	0.28	1.88
TRL	912107	300	-1.384856	-0.004616	0.72	-1.385876	-0.004620	0.79	1.78
BASt	AC-H36	50	0.670842	0.013417	0.98	0.672719	0.013454	0.93	8.55
BASt	AC-H48	50	0.673019	0.013460	0.97	0.674739	0.013495	0.91	8.71
TRL	*912042 Wood*	*300*	*-1.331751*	*-0.004439*	*1.22*	*-1.331895*	*-0.004440*	*1.23*	*1.80*

5.3 Wall Flatness

The wall flatness is mainly (or even only) an issue in case when a barrier with deformable element is used in front of the LCW. The barrier is backed by a plate of about 2 mm thick which spreads the loads between cells which are not aligned. Although non-alignment of cell faces can (at least partially) be compensated by adjusting the protective layers on the cells it was decided to collect flatness data from a number of existing walls and based on this define requirements for this parameter.

5.3.1 Approach

A protocol to measure the position of cells using the FARO arm was prepared by Humanetics. The FARO arm was suggested as it is available in most laboratories to accurately measure dummy positioning before a crash tests. It has sufficient range to cover an entire LCW from a single initial position.

The protocol was transferred into an Excel file which requires input on reference position of the FARO arm and measured positions in 3 dimensions form each cell. See Figure 5.9. Info on the cell centre and the corners was to be provided.

Three laboratories participated in this task: BASt, IDIADA and TRL. The measured data were processed by Humanetics and an analysis of the influence of the flatness on the test outcome was made using data from trolley tests done by BASt.

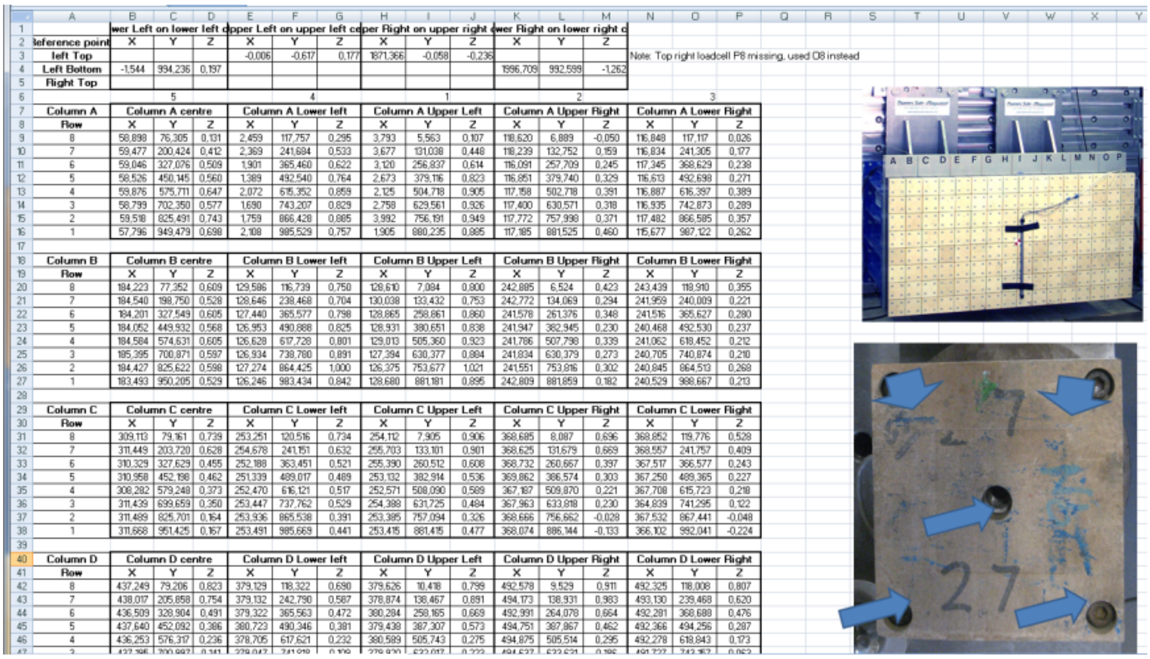


Figure 5.9: Excel file used to collect measurement data on wall flatness.

5.3.2 Wall Flatness Results

Both BASt and TRL provided multiple measurements, TRL doing three repeats on the wall itself and one measurement with protective layer. BASt did two repeats on the wall itself and one measurement with protective wooden layer on the cells. As a first step the repeated measurements were processed to give average results over the measurements. Next an average depth of the wall was computed by summing the depth position of all cells at centre location and dividing by the number of cells. This average depth was subtracted from the measured depth location at centre and corner positions to give variations over the barrier. Results for the IDIADA wall are shown in Figure 5.11. The row and column numberings used are indicated in Figure 5.10. Depth positions relative to the average plane are shown for the cell centres. The left graph plots results column wise while the right graph gives results per row. It is noted that for the columns sometimes the indication A through P is used and sometimes 01 through 16. For the final protocol it is suggested to apply the load cell numbering and indication as included in the right graph of Figure 5.10 assuming numbering 01 – 16 for the columns.

From Figure 5.11 it can be seen that cell to cell centre locations show a variation of about ±1 mm over the entire wall. In the IDIADA wall differences per column (left graph) appear to be relatively small compared to variations over the row (right graph). This is explained by the construction of the wall. The cells are mounted first on back-plates covering a column and subsequently assembled into the barrier.

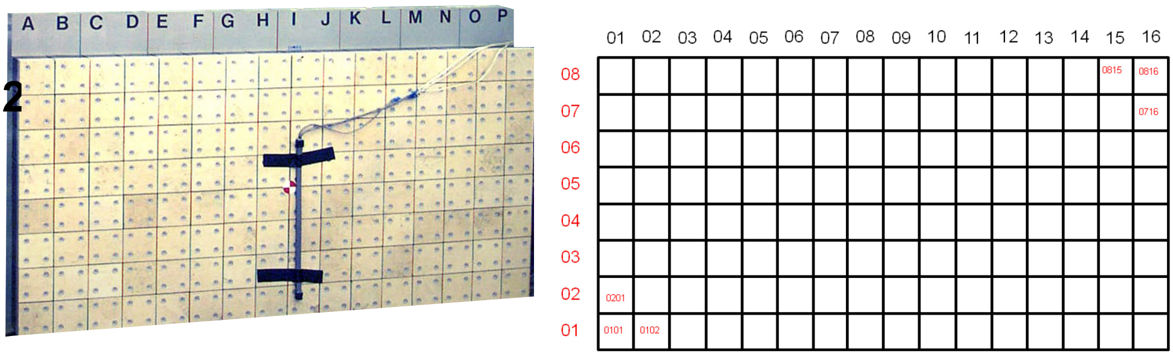


Figure 5.10: Load cell numbering (16 columns and 8 rows)): left picture of wall with columns indicated as A through P; right proposed cell numbering with columns indicated as 01 through 16. Row numbers are always indicated as 1 through 8.

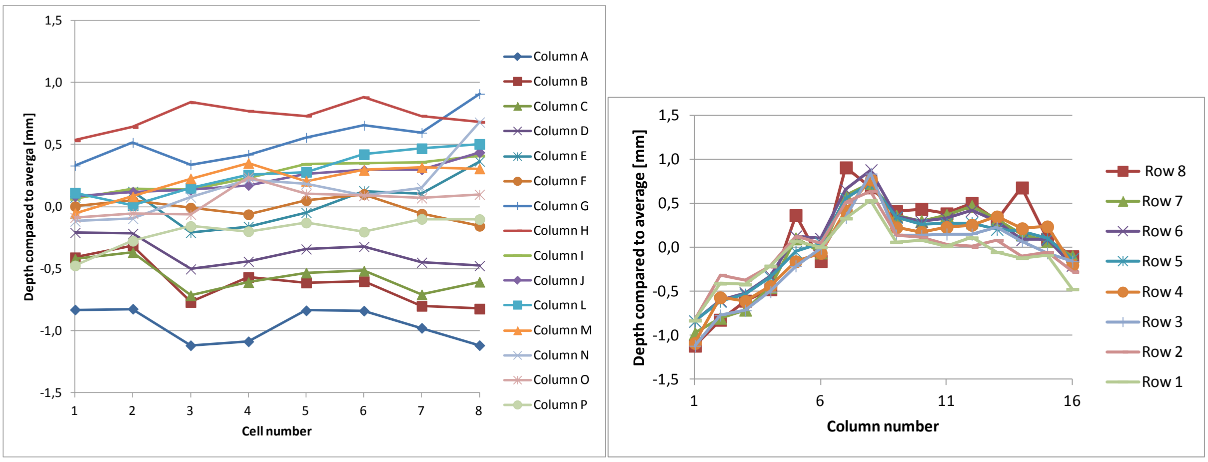


Figure 5.11: Flatness results IDIADA wall: depth position of center of all cells. Left graph shows results for each column (8 cells per column); right graph shows results for each row (16 columns).

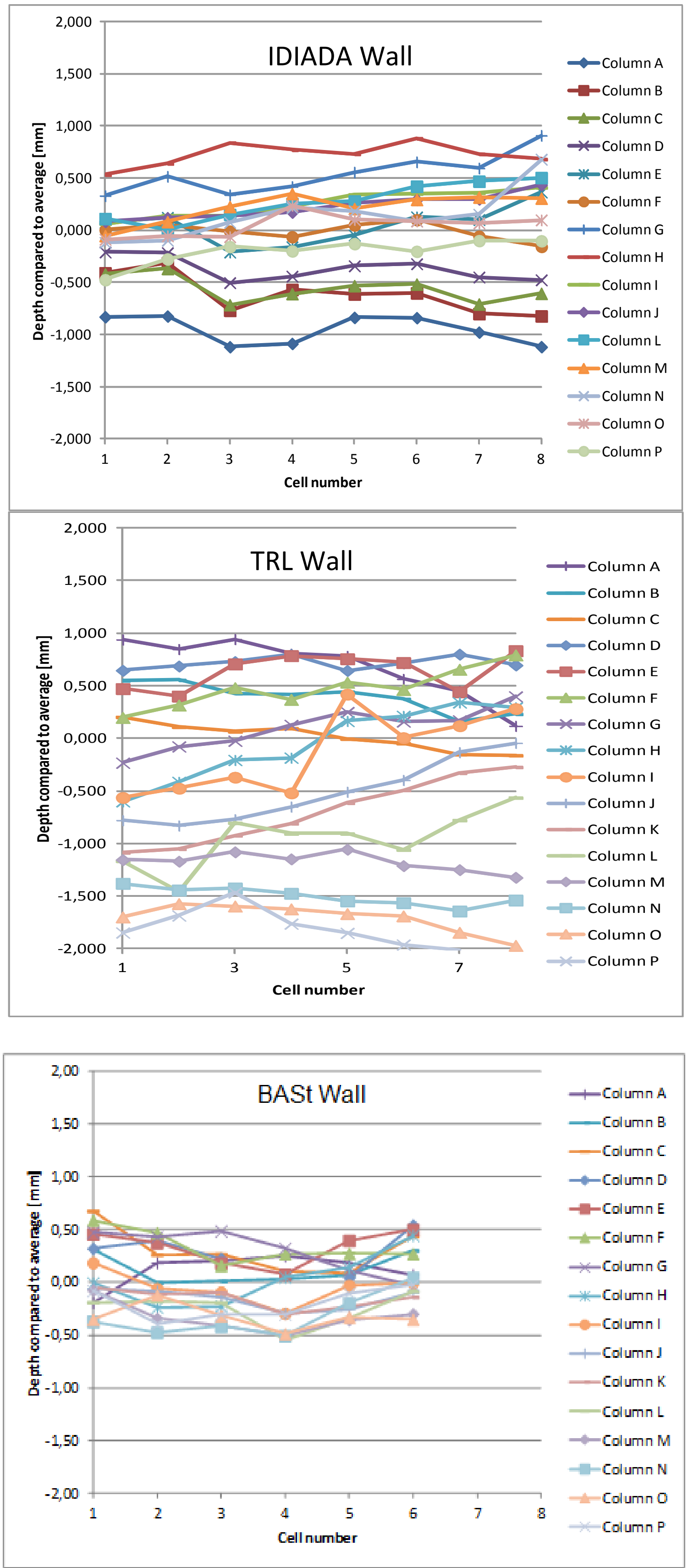
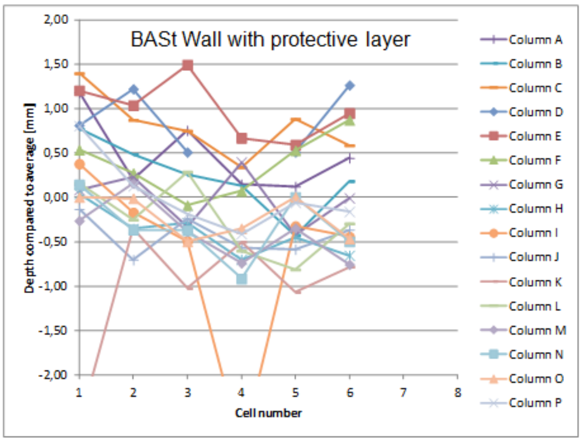


Figure 5.12: Flatness results of all three walls.

Results for all three walls measured are given in Figure 5.12. Although some variations exists between the walls all show a small variation in overall depth of less than 3 mm. Note that the BASt walls only has 6 cells over the height of each column while the TRL and IDIADA barriers have 8 cells in each column.

The influence of protective layers was measured in the TRL wall and the BASt wall. Results are shown in Figure 5.13. For the BASt wall the variations in depth increase when adding the protective wooden layer to the cells (compared to measurements on the wall itself) while for the TRL wall variations remain almost identical or even reduce somewhat. The latter is explained by the fact that TRL is minimising depth variations for full width barrier tests using protective layers from MDF of different depths.

Table 11 shows maximum differences in depth positions between adjacent cells. These differences are taken along horizontal, vertical and diagonal lines. Values are provided for centre to centre and corner to corner locations. Except for the BASt wall with protective layer the maximum variations in depth between cells appears to be around 1 mm.



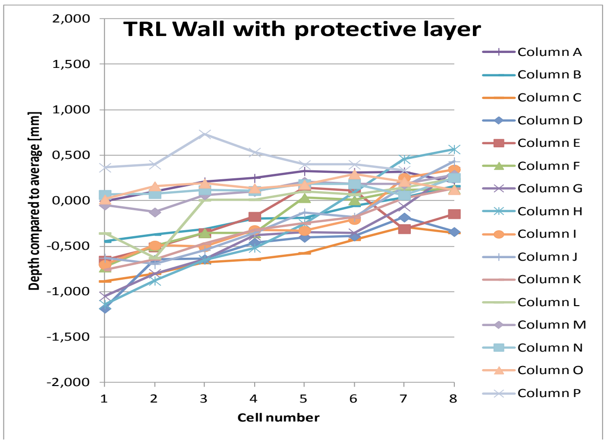


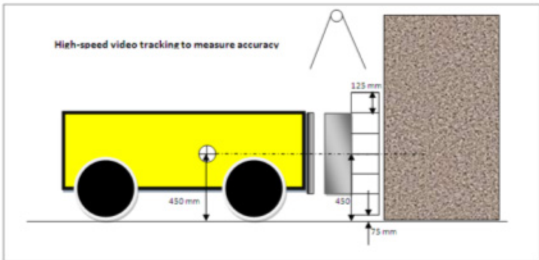
Figure 5.13: Flatness results with protective layer of BASt and TRL walls.

Table 11: Maximum differenced in depth position between adjacent cells.

	IDIADA	BASt	BASt With protective layer	TRL	TRL With protective layer
Centre-Centre	1,06	0,80	2,70	0,95	0,64
Corner - Corner	0,66	0,94	4,07	1,01	0,95

5.3.3 Analysis of Trolley Tests BASt

To analyse the influence of wall flatness FIMCAR partner BASt conducted a test using a trolley with flat loading plate. The trolley impacted a honeycomb barrier attached to the wall. The barrier was partitioned in a left side and a right side. Figure 5.14 shows the configuration. In total five tests were done. The influence of variations in cell depth position was investigated using results of a test at an impact speed of 15 km/h.



Test no.	Velocity km/h	Wood plate
FM02LC01	15	No
FM02LC02	15	No
FM02LC03	15	Yes
FM02LC04	20	Yes
FM02LC05	25	Yes

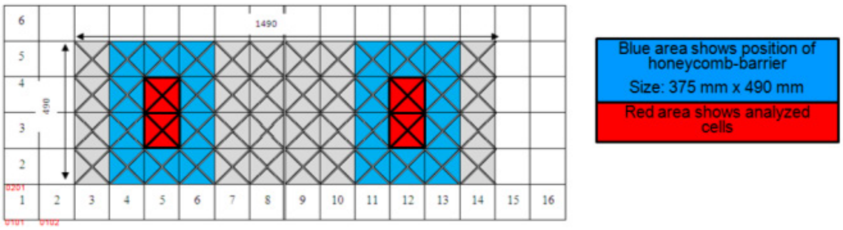


Figure 5.14: Configuration of trolley tests performed by BASt.

The two barrier partitions covered an area of 3 horizontal by 4 vertical cells each. To exclude edge effects the resulting forces of the inner cells in the left and right partition were analysed. See cells indicated with red colour in Figure 5.14.

Figure 5.15 gives force histories for the left and right barrier cells, measured depth position and peak forces. Force time histories for the cells on the left and right barrier show only very minor differences. Peak forces in the left barrier are 7.11 kN and 7.19 kN. In the right barrier slightly higher peak forces of peak forces of 7.23 kN and 7.27 kN were found. It is notable that the peak forces in the right barrier partition are higher while the cells are located more inward: -0.54 mm and -0.19 mm compared to 0.07 mm and 7.19 mm for the left barrier. This contradicting result is explained by the fact that the trolley did not approach the barrier fully orthogonal. Detailed analysis of the high speed films showed that the right side was impacting the barrier slightly before the left side, explaining the difference.

The above result shows that the load cell flatness is only a single factor in an overall measurement chain affecting the accuracy. Other parameters like approach angle and barrier flatness also influence the results. Information of the barrier flatness was requested at suppliers of these tools but not obtained.

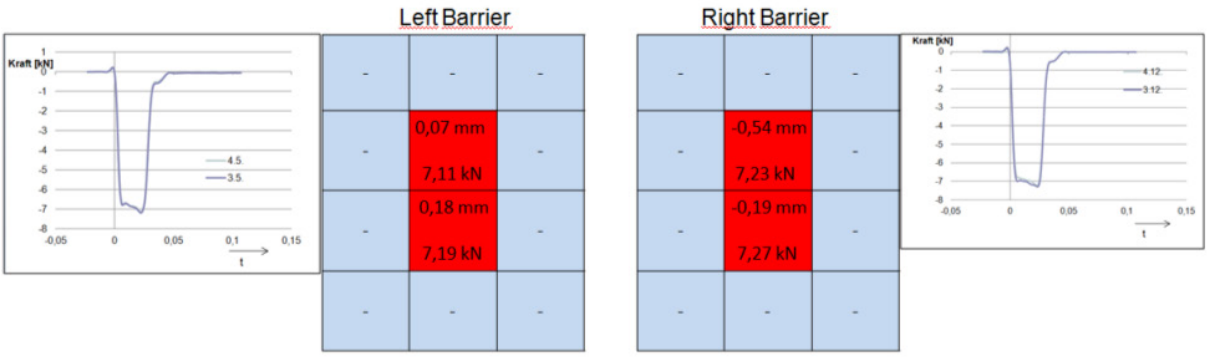


Figure 5.15: Forces in center cells of left and right barrier, peak forces and cell depth position (values indicated in cells marked in red).

5.3.4 Discussion

Measurements on various load cell walls showed that existing tools have an overall variation in depth between cells of less than 3 mm. Adjacent cells have depth variations of about 1 mm. The latter value is identical for centre to centre and corner to corner positions.

Analysis of trolley tests with a flat impacting surface showed that peak forces in the cells do not correlate with depth position of the cells. Other factors like approach angle of the impacting surface and honeycomb flatness affect results to such an extent that depth position of the cells cannot be linked to peak forces observed.

Based on the above it is decided to adopt the measured depth variations into the protocol defining the crash wall. The measured depth variations appear to be feasible / achievable and influence on measured force distribution is small compared to other factors in the test.

The definition of the load cell wall including the requirements on wall flatness is included in Annex B. Other requirements like cell size, ground clearance, cell numbering are straightforward and did not need any further investigations.

5.4 Conclusions

As part of FIMCAR Task 3.2 a Load Cell Wall (LCW) certification procedure was defined. The procedure consists of the LCW definition and certification requirements in terms of wall flatness. In addition a specification and calibration protocol was prepared for the transducers.

Parameter values for both documents were obtained from measurements and analyses on Load Cell Walls and transducers itself. Certification requirements for the wall flatness were based on measurements of three existing walls and an analysis of a trolley test done by BASt. A series of load cells was tested to check and refine values set for non-linearity and hysteresis.

The protocols are included in the Annex A and Annex B of this report.

6 VALIDATION OF FULL WIDTH DEFORMABLE BARRIER PROTOCOL

6.1 Validation of Concept

In this section the performance of cars in car-to-car tests is compared with their assessment in the FWDB test. To validate the FWDB test and proposed performance limits it is expected that if the car meets the proposed performance limits in the FWDB test then it should perform well in the car-to-car test as regards structural alignment and vice versa.

6.1.1 Supermini 1 Test Series

The Supermini 1 was tested in both FWDB tests and car-to-car tests. The objective was to validate that good/poor performance in car-to-car tests in terms of structural vertical alignment correlated with meeting/not meeting the proposed FWDB metric performance limits.

The FWDB and car-to-car tests that were performed are shown in Table 12 and Table 13. The heights of the bumper crossbeams in the Supermini 1 tests are shown in Figure 6.1.

Table 12: Supermini 1 FWDB test matrix.

Test number	Ride height test condition	Bumper crossbeam height (corrected for impact accuracy)		Nominal test speed (km/h)
		Bottom	Top	
FM04C3FW	Standard	451	530	56
FM05C3FW	Standard	449	528	56
17459	Standard	449	528	56
114601FF	Lowered	413	492	56
F114202	Raised	482	561	56

Table 13: Supermini 1 car-to-car test matrix.

Alignment	Nominal test speed (km/h)	Nominal offset (%)
Aligned structures	56	50
Misaligned structures	56	50

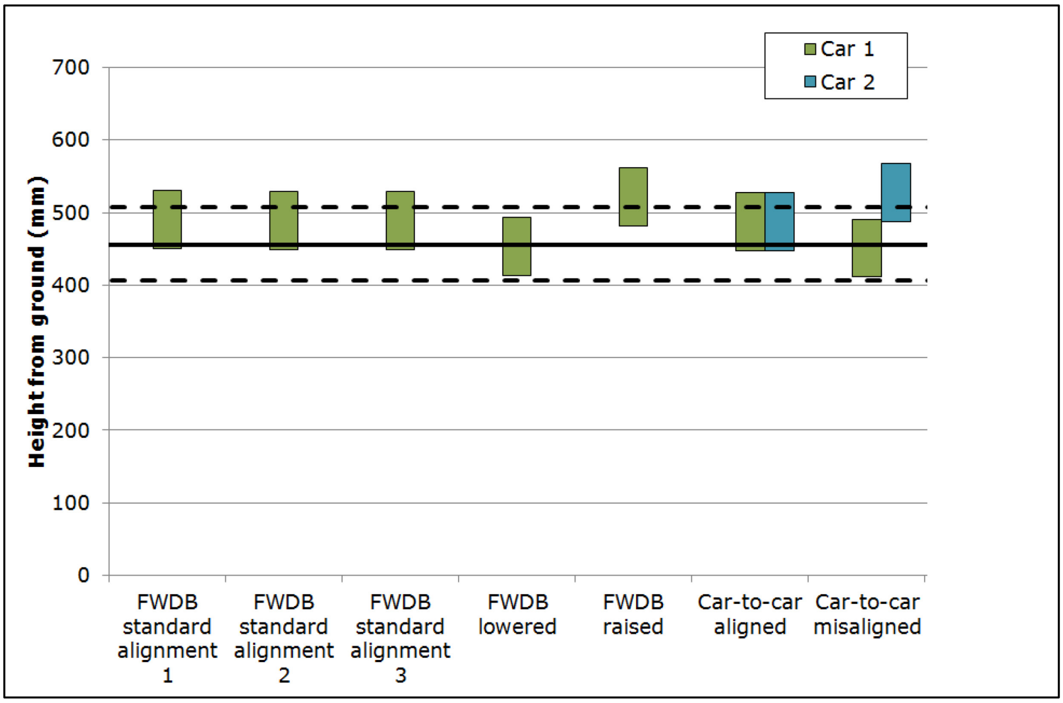


Figure 6.1: Heights of bumper crossbeams in Supermini 1 tests.

Figure 6.2: shows the intrusions in the Supermini 1 car-to-car tests.

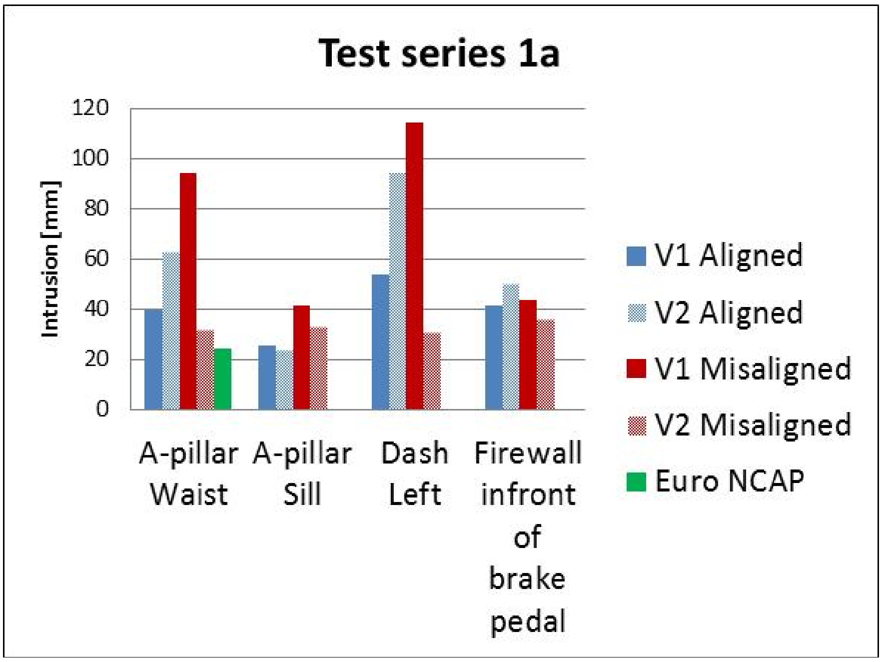


Figure 6.2: Intrusions in Supermini 1 car-to-car tests [Sandqvist 2013].

The results of this test show that the peak intrusions in the aligned test were lower than in the misaligned test at the A-pillar waist, A-pillar sill and dash, and slightly higher at the firewall in front of the brake pedal. This shows that the vehicles in the aligned test performed better than in the misaligned test.

Figure 6.3 shows the dummy injury criteria in the Supermini 1 car-to-car tests.

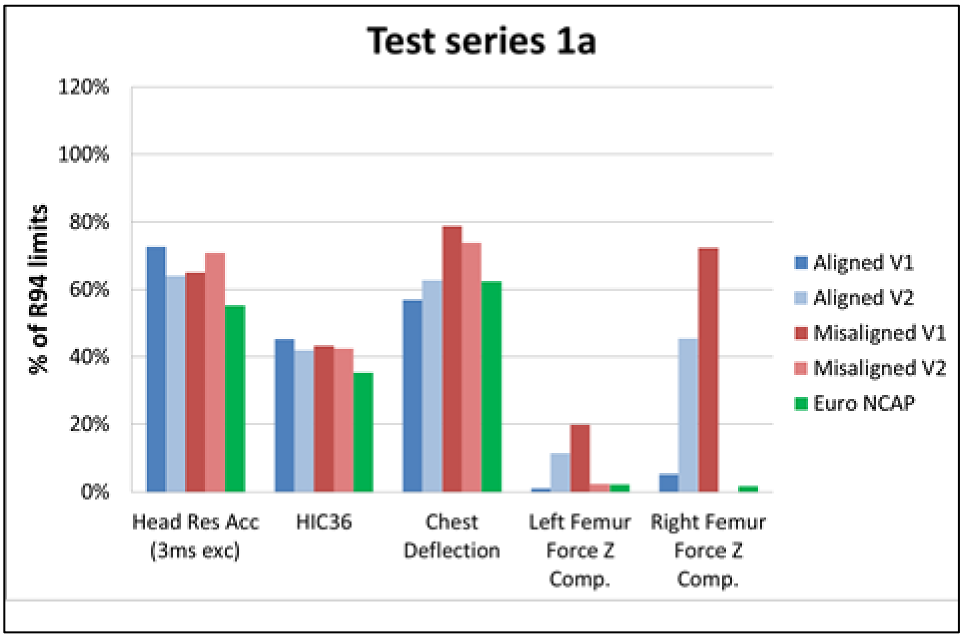


Figure 6.3: Dummy injury criteria in Supermini 1 car-to-car tests [Sandqvist 2013].

The results show that the injury criteria for the head are similar in the aligned and misaligned tests, but the chest deflection and femur forces are higher in the misaligned test. This shows that the vehicles performed better in the aligned test than in the misaligned test.

The results from a standard Supermini 1 FWDB test are shown in Table 14. The results from the lowered Supermini 1 FWDB test are shown in Table 15. The results from the raised Supermini 1 FWDB test are shown in Table 16. The standard tests and the lowered test were both performed with the vehicle frontal structures in line with the common interaction zone. The raised test was performed with the frontal structure in partial alignment with Row 4, but not in alignment with Row 3.

Table 14: Supermini 1 (standard) FWDB results.

	Supermini 1 FWDB, FM04C3FW		
	Value	**0.2*Ft40**	**OK/NOK**
F3 > MIN[100, 0.2Ft40]	104	80,4	OK
F4 > MIN[100, 0.2Ft40]	103	80,4	OK
Global	OK		

Table 15: Supermini 1 (lowered) FWDB results.

	Supermini 1 FWDB, 114601FF		
	Value	**0.2*Ft40**	**OK/NOK**
F3 > MIN[100, 0.2Ft40]	124.4	85.9	OK
F4 > MIN[100, 0.2Ft40]	112.5	85.9	OK
Global	OK		

Table 16: Supermini 1 (raised) FWDB results.

	Supermini 1 FWDB, F114202		
	Value	0.2*Ft40	OK/NOK
F3 > MIN[100, 0.2Ft40]	62.9	79.7	NOK
F4 > MIN[100, 0.2Ft40]	122.8	79.7	OK
Global	NOK		

In summary, the results show that the vehicle passes the FWDB metric in tests where the vehicle main structures (PEAS) are in line with the common interaction zone and the vehicle fails the FWDB metric when the vehicle PEAS is not in alignment with the common interaction zone. The car-to-car tests show a better performance when the vehicle main structures (PEAS) are aligned compared to when they are not aligned. These results validate the 'force in a common interaction zone' concept and with the FWDB test results show that the proposed FWDB metric can be used to enforce it.

6.1.2 Supermini 2 test series

The Supermini 2 was tested in both FWDB tests and car-to-car tests. The FWDB and car-to-car tests that were performed are shown in Table 17 and Table 18.

Table 17: Supermini 2 FWDB tests.

Test number	Ride height test condition	Bumper crossbeam height (corrected for impact accuracy)		Nominal test speed (km/h)
		Bottom	Top	
17423	Standard	401	514	56
FM08F5FW	Standard	401	514	40

Table 18: Supermini 2 car-to-car tests

Alignment	Nominal test speed (km/h)	Nominal offset (%)
Aligned structures	56	50
Misaligned structures	56	50

The results from the FWDB test at 56km/h are shown inTable 19.

Table 19: Supermini 2 56km/h FWDB results

	Supermini 2, 17423			
	Value	**0.2*Ft40**	**MIN[100, 0.2Ft40]**	**OK/NOK**
F3 > MIN[100, 0.2Ft40]	140.1	108.7	100	OK
F4 > MIN[100, 0.2Ft40]	148.1	108.7	100	OK
Global	OK			

The results from the FWDB test show that the Supermini 2 passes the FWDB metrics by a significant margin. This indicates that the vehicle has adequate structure in alignment with the common interaction zone. In addition the load in Row 2 is high enough to allow the limit reduction part of the metric to be invoked. This indicates that the Supermini 2 also has a good subframe load path.

Figure 6.4 shows the vehicle accelerations in the Supermini 2 car-to-car and Euro NCAP tests. Figure 6.5 shows that dummy injury criteria in the Supermini 2 car-to-car tests.

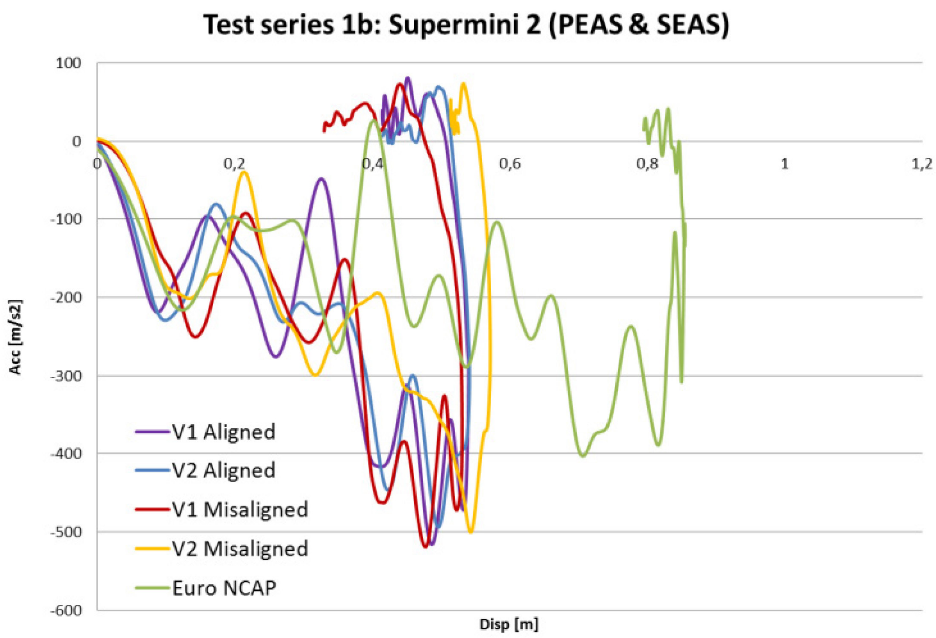


Figure 6.4: Supermini 2 vehicle accelerations in car-to-car and Euro NCAP tests.

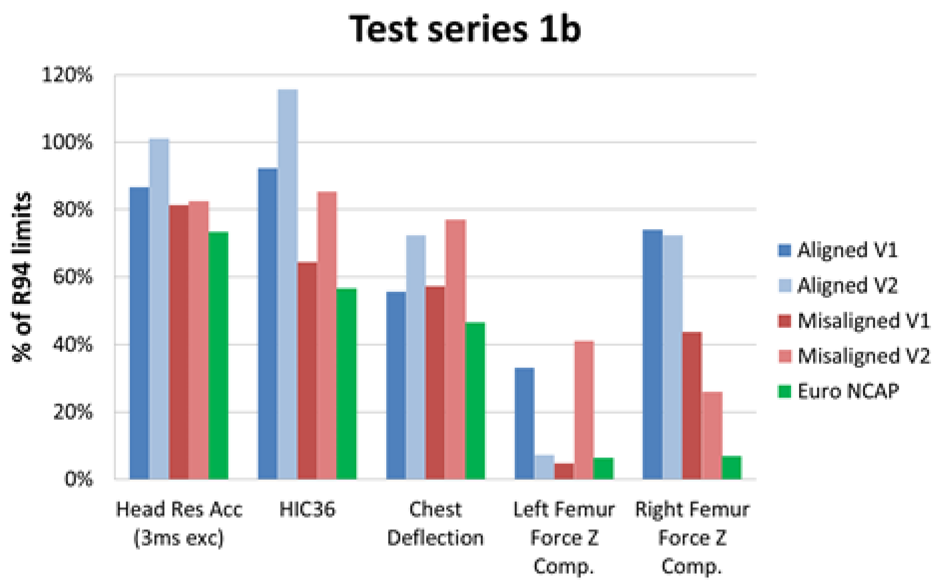


Figure 6.5: Supermini 2 dummy injury criteria.

The results show that in the car-to-car tests the vehicle accelerations were very high. This indicates that the frontal structures of the Supermini 2 are very stiff. This explains why the dummy injury criteria are higher in the aligned tests than in the misaligned tests.

If the vehicle had been designed to pass a FW test, then it is likely that the dummy numbers would have been lower in the aligned test due to improved occupant restraints and/or reduced stiffness of the frontal structures to pass the FW test.

In summary, the smaller difference in the intrusions between the aligned and misaligned tests for the Supermini 2 compared to the Supermini 1 illustrate the advantage of a design which spreads load vertically as described in greater detail in FIMCAR Deliverable D6.1 [Sandqvist 2013]. The results shown above demonstrate that the proposed FWDB metric for structural alignment correctly assesses the Supermini 2 as having structures in alignment with the common interaction zone and with the limit reduction part of the metric encourages the subframe load path which was shown to work well in the car-to-car tests.

6.1.3 SUV Test Series

In an SUV test series two different kind of SUVs were tested in car-to-car crashes against the Small Family Car 1. The objective of these test series was to show the differences between an SUV with one load path and an SUV with two load paths.

The SUV 1 was tested in both FWDB tests and car-to-car tests with a Small Family Car 1. The FWDB and car-to-car tests that were performed are shown in Table 20 and Table 21.

Table 20: SUV 1 FWDB tests.

Test number	Ride height test condition	Bumper crossbeam height (corrected for impact accuracy)		Nominal test speed (km/h)
		Bottom	Top	
B4767	Standard	522	609	56

Table 21: SUV 1 car-to-car tests.

Alignment	Impact partner	Nominal test speed	Nominal offset
Aligned structures	Small Family Car 1	56 km/h	50 %
Misaligned structures	Small Family Car 1	56 km/h	50%

The height of the main structure (PEAS) of the SUV 1 aligns with the upper part of Row 4 of the LCW, and none of it aligns with Row 3. However, the SUV 1 does have a secondary structure (SEAS) which aligns with Row 3 and lower rows. The results from the FWDB test are shown in Table 22.

Table 22: SUV 1 FWDB results.

	SUV 1, B4767			
	Value	**0.2*Ft40**	**MIN[100, 0.2Ft40]**	**OK/NOK**
F3 > MIN[100, 0.2Ft40]	151	135.4	100	OK
F4 > MIN[100, 0.2Ft40]	192	135.4	100	OK
Global	OK			

The results show that the SUV 1 at its standard ride height has sufficient structure in alignment with the common interaction zone (Rows 3 and 4) to meet the metric requirements. The intrusions and dummy injury criteria in the car-to-car tests are shown in Figure 6.6 and Figure 6.7 respectively.

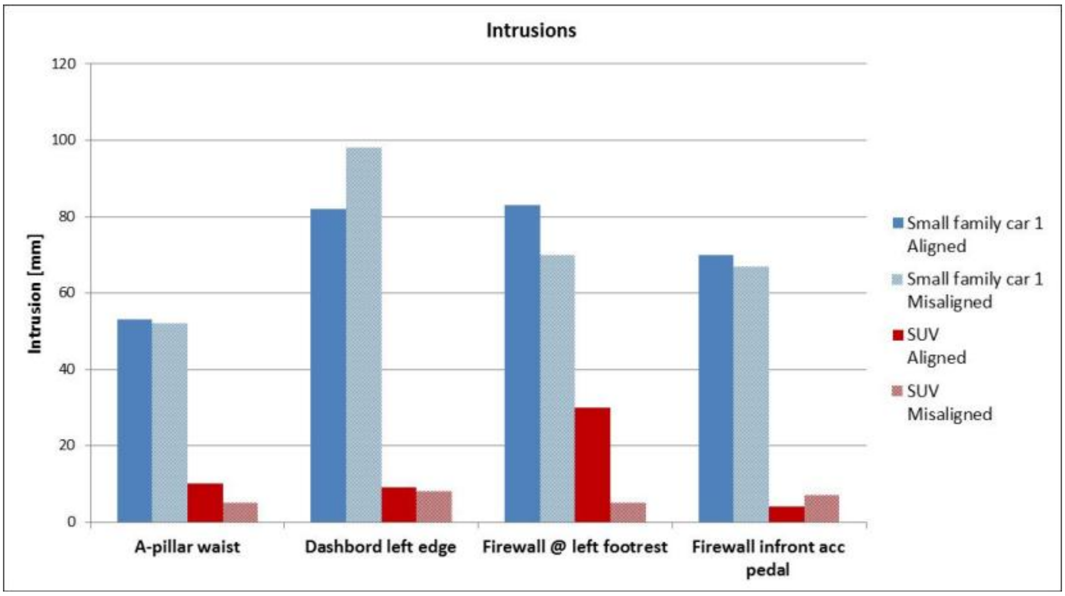


Figure 6.6: Intrusions in SUV 1 – Small Family Car 1 car-to-car tests [Sandqvist 2013].

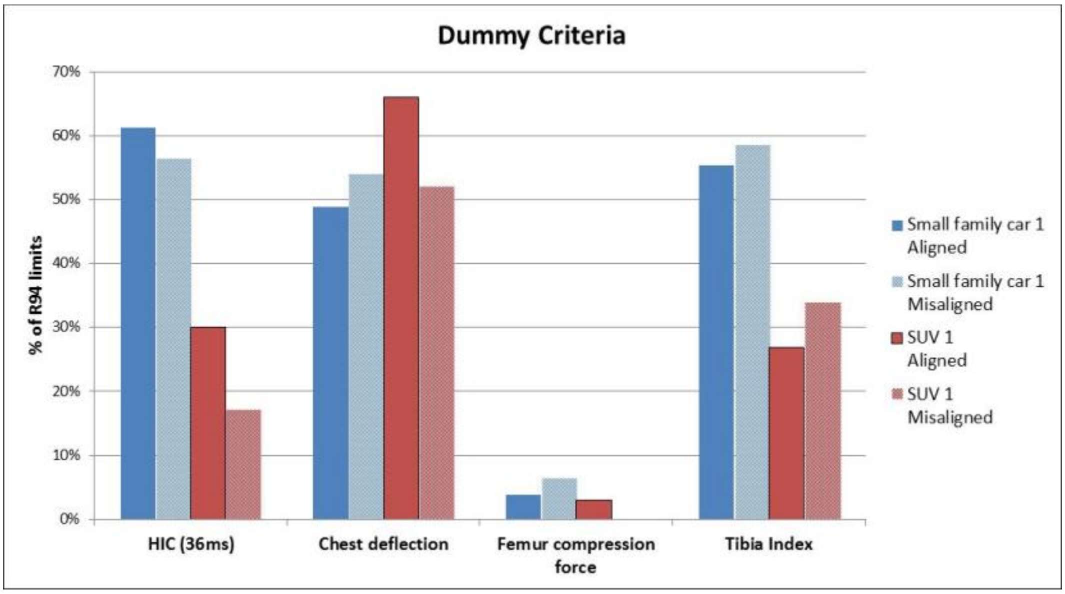


Figure 6.7: Dummy injury criteria in SUV 1 - Small Family Car 1 car-to-car tests [Sandqvist 2013].

The results show that there is a general similar level of intrusion and dummy injury criteria in both the aligned and misaligned test. This shows that the SEAS structures are strong enough to provide adequate structural interaction capability in a car-to-car impact. This agrees with the FWDB metric assessment of the SUV 1 and hence validates the proposed metric. An FWDB with a SUV 2 and car-to-car test with a SUV 2 and Small Family Car 1 were performed. The tests performed are shown in Table 22 and Table 24.

Table 23: SUV 2 FWDB test.

Test number	Ride height test condition	Bumper crossbeam height (corrected for impact accuracy)		Nominal test speed (km/h)
		Bottom	Top	
123514FF	Standard	475	-	56

Table 24: SUV 2 car-to-car test

Alignment	Impact partner	Nominal test speed	Nominal offset
Aligned structures	Small Family Car 1	56 km/h	50%
Misaligned structures	Small Family Car 1	56 km/h	50%

The SUV 2 has primary structures (PEAS) in the upper part of Row 4. The SUV 2 has no additional structures (SEAS) in Row 3 or lower. The results of the FWDB test are shown in Table 23. These results show that the SUV 2 fails the FWDB metric as the force levels in Row 3 are not sufficient.

Table 25: SUV 2 FWDB results

	SUV 2, 123514FF			
	Value	0.2*Ft40	MIN[100, 0.2Ft40]	OK/NOK
F3 > MIN[100, 0.2Ft40]	66	334.6	100	NOK
F4 > MIN[100, 0.2Ft40]	534	334.6	100	OK
Global	NOK			

In the car-to-car test the SUV 2 PEAS overrode the Small Family Car 1 and impacted the gearbox of the Small Family Car 1. This caused the gearbox to rotate which caused increased local intrusion in the footwell area. This validates the FWDB result as there was not enough suitable structure in line with the common interaction zone.

6.1.4 Effect of Test Speed on Metric

In FIMCAR most tests with the FWRB and FWDB test procedures were conducted with a speed of 56 km/h (Europe) or 55 km/h (Japan), respectively. During the project it became clear that a lower test speed with 50 km/h for AIS 3 level would be better in terms of injury mitigation to not just address the high speed impacts but also the high proportion of impacts with lower severity. This is further explained in Chapter 4.2.

Therefore it was decided that in the final test procedure 50 km/h is the test speed for FWRB and FWDB.

Nevertheless it was decided to conduct all pending full width crash tests in FIMCAR with 56 km/h in order to compare the existing test data with new test data. Simulations were conducted during the project with the PCM simulation models from TU Berlin and the GCM simulation models from CRF to investigate the differences on the metric which occur due to various test speeds. Additionally, a full scale test was conducted with a Supermini 2 at 40 km/h.

6.1.4.1 **Simulations with PCM Models**

In WP 3 the simulation request 10 was defined to investigate the test severity for FWDB by comparing FWRB pulses with 50 km/h and FWDB pulses with 56 km/h, 50 km/h and 40 km/h. Therefore simulations with the PCM models of FWRB and FWDB tests were conducted to analyse the influence on the compatibility metrics with decreased test severity.

The model taken for these simulations is shown in the Figure 6.8. The geometric alignment was chosen that the vehicle should pass based on the US voluntary agreement. The longitudinals were in the common interaction zone.

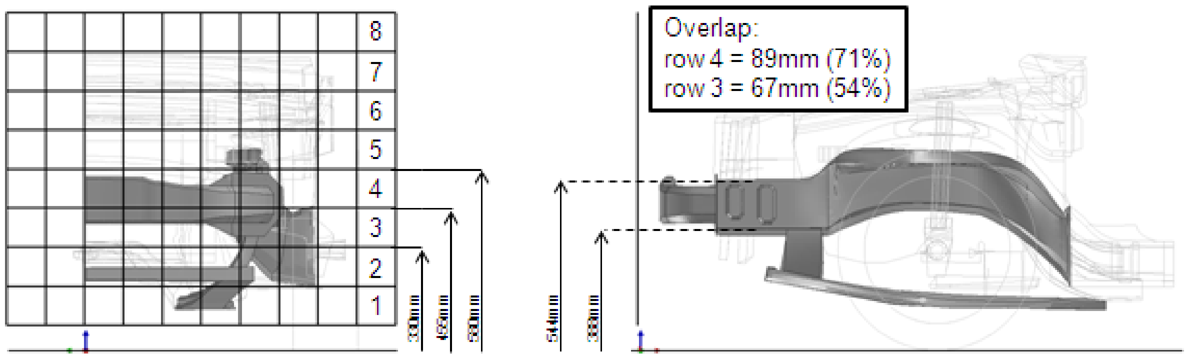


Figure 6.8: Test configuration for the simulations with different test speeds

The simulations results with the PCM model at 56, 50 and 40 km/h are displayed in the following Table 26. The forces at the LCW were calculated with the metric without Limit Reduction, see Figure 4.1.

Table 26 Results of the FWDB simulations with 56, 50 and 40 km/h

		FWDB_56	FWDB_50	FWDB_40
Metric as defined in Figure 4.1 up to 40ms	F_{t40} [kN]	**588.2**	**487.4**	**272.3**
	0.2 * F_{t40} [kN]	**117.6**	**97.5**	**54.5**
	F3 [kN]	**182.7**	**153.4**	**80.7**
	F4 [kN]	**198.2**	**149.2**	**87.5**

It is obvious that the total LCW force up to 40 ms decreases with a lower test speed. However, as this metric uses relative numbers (20% of F_{t40}) the vehicle passes the metric at all test speeds.

In the next Figure 6.9 the force distribution of Row 3 and 4 up to 40 ms in the FWDB simulations is shown in a graph. The sum forces of Row 3 and 4 of each configuration were set to 100 %. Although the main force decreases with a lower test speed, the force distribution stays on a very similar level.

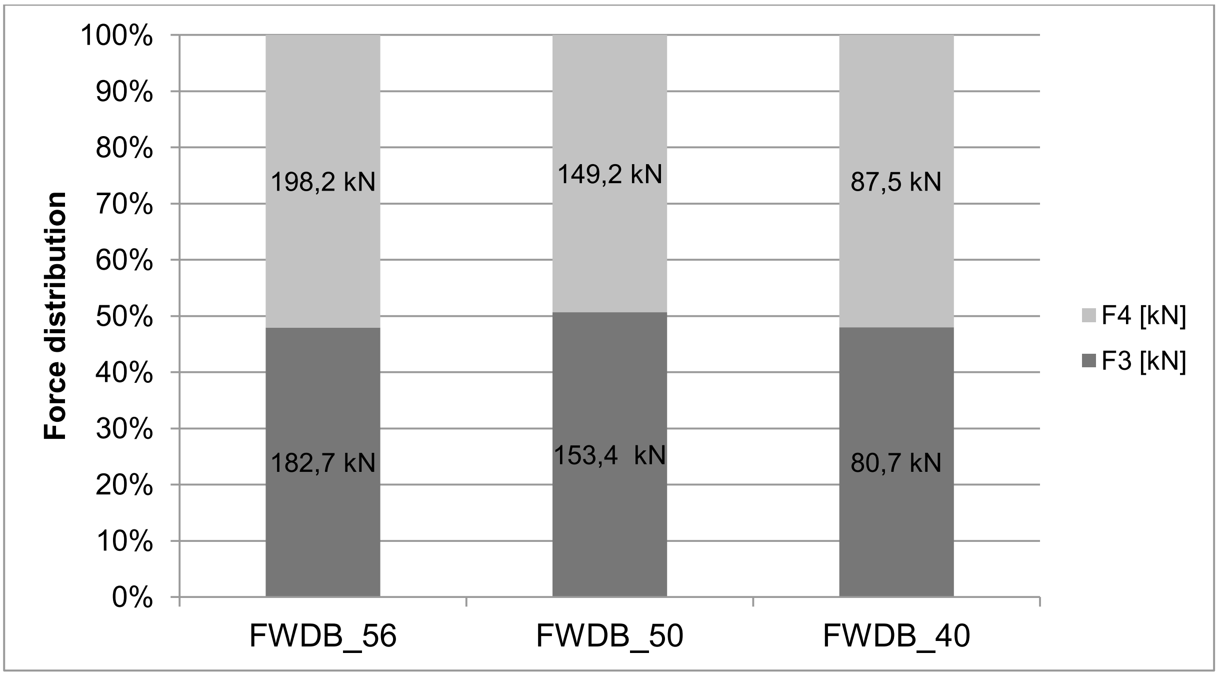


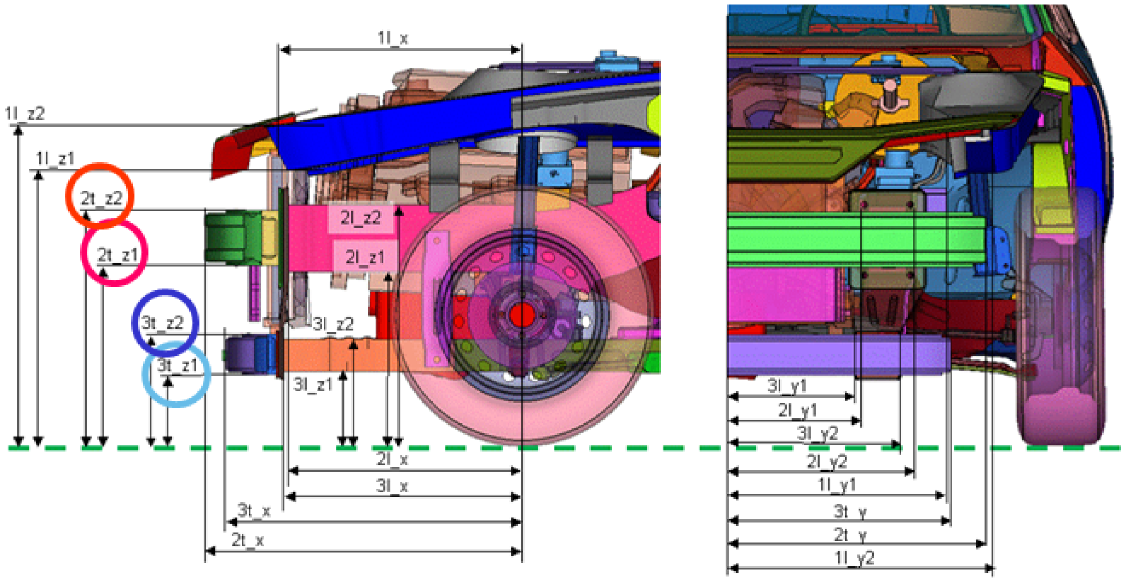
Figure 6.9: Force distribution of Row 3 and 4 up to 40 ms in FWDB simulations (sum of Row 3 and 4 of each configuration is set to 100 %).

In summary it can be concluded that the metric tends to work also for lower velocities. The LCW sum forces (F_{max}) decreases with decreasing velocity. Sum forces of Row 3 and 4 and the row forces up to 40 ms are almost the same for the different velocities.

6.1.4.2 **Simulations with GCM Models**

The same investigations were done with the GCM models from CRF. Therefore numerical simulation results of GCM1B, GCM2A and GCM3A against the FWDB barrier including the LCW were conducted at the impact speeds 40, 50 and 56 km/h. The aim was to compare the row and total load versus time curves, the maximum row loads up to 40 ms and the effect on the metric.

The following Figure 6.10 shows the geometries for the different GCM models GCM1B, GCM2A and GCM3A. All models were multiple load path designs with a PEAS structure in height of Row 3 and Row 4 and a SEAS structures in height of Row 2 and 1. In addition all models have their PEAS in alignment with the US voluntary agreement. Therefore they should pass the FWDB metric at all test speeds.



CROSSBEAMS	2t_x	3t_x	2t_y	3t_y	2t_z1	2t_z2	3t_z1	3t_z2
GCM-1A	776	X	649	X	394	498	X	X
GCM-1B	776	738	649	507	394	498	239	284
GCM-2A	750	563	607	490	442	555	172	233
GCM-2B	750	X	607	X	442	555	X	X
GCM-3	749	698	610	528	430	563	171	268

Figure 6.10: Geometries for the GCM models GCM1B, GCM2A and GCM3A.

The following Table 27 shows the results of the comparison. The maximum row loads are calculated for Rows 1, 2, 3 and 4 up to 40 ms for the impact speed 40, 50 and 56 km/h. Additionally, the maximum total LCW force up to 40 ms was calculated in order to compare the performance of the FWDB metric.

Table 27: GCMs vs. FWDB (LC) @ different impact speeds, max row loads up to 40 ms.

		Generic Car Model								
	FWDB LCW	GCM1B			GCM2A			GCM3A		
	Impact speed [kN]	40 km/h	50 km/h	56 km/h	40 km/h	50 km/h	56 km/h	40 km/h	50 km/h	56 km/h
Max Row Load Up to 40 ms [kN]	F4	82.37	97.44	148.67	128.4	170.4	185.92	164.69	194.64	214.38
	F3	104.41	129.57	161.36	100.17	115	123.83	122.42	155	163.33
	F2	78.4	92.08	90.75	49.71	61.06	96.2	81.26	113.87	122.59
	F1	27.42	30	32.45	58.31	66.87	70.34	48.88	49.45	56.03
Max Total LCW Load Up to 40 ms [kN]	F_{T40}	353.97	425.45	499.59	445.87	542.93	623.9	584.75	725.97	800.15
Metric (3)	$0.2*F_{T40}$	70.79	85.09	99.92	89.17	108.59	124.78	116.95	145.19	160.03
	Metric Reference Value	70.79	85.09	99.92	89.17	100.00	100.00	100.00	100.00	100.00

In total the results were very comparable with the results from the PCM models explained in chapter 6.1.4.1 Simulations with PCM models. The maximum row loads are decreasing when the impact speed is reduced. However, all GCM models pass the FWDB Metric at each impact speed considered. An additional results was that the total load in the first two Rows (F1+F2) is relevant. The presence of the structural lower load paths of GCMs is detected by the barrier.

In order to address the FWDB metric with Limit Reduction the PCM simulations were analysed taking into account the row loads of Row 3 and 4 but also of Row 2, see Figure 6.11. It is obvious that the share of the loads applied to Rows 2, 3 and 4 stays almost unchanged while the absolute values are dependent of the test speed.

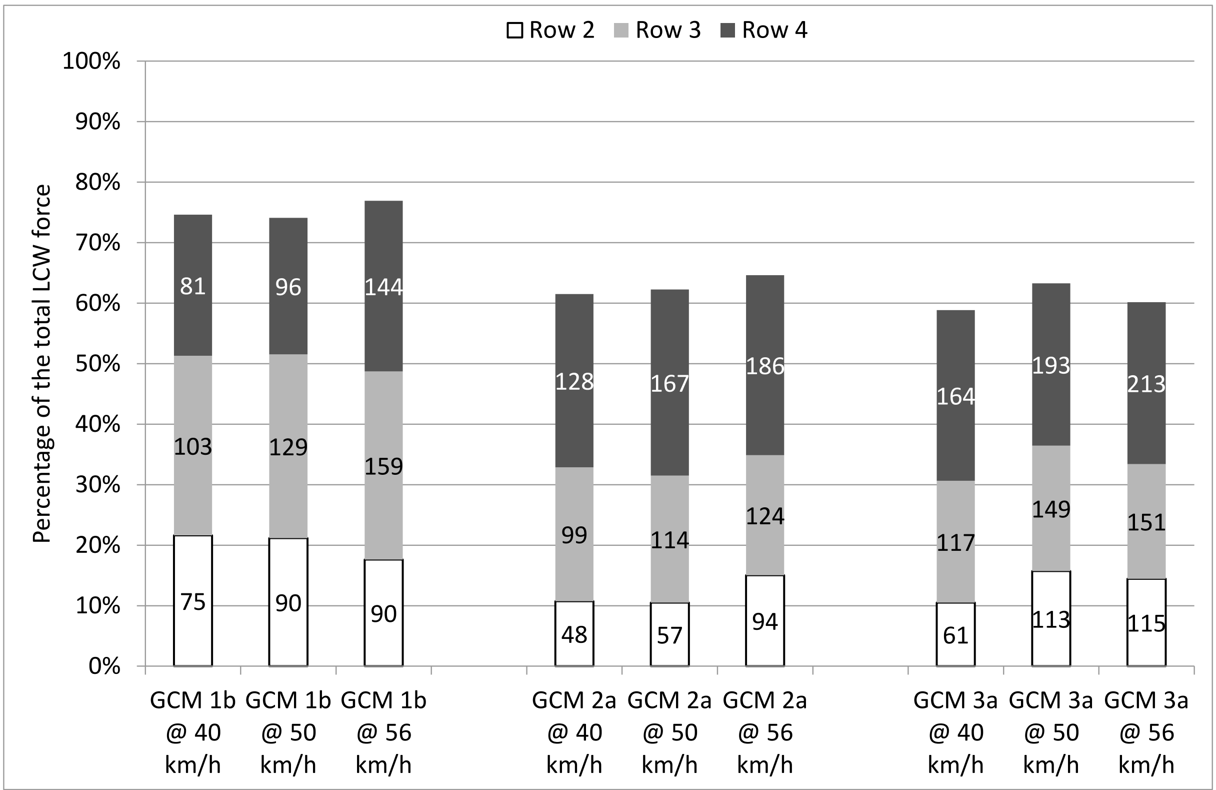


Figure 6.11: Share of loads in Rows 2, 3 and 4 dependent on test speed for GCM 1B, 2A and 3A.

6.1.4.3 **Summary**

With different simulation models it could be shown that the metric as explained in Chapter 4.1 works for test speeds in a range from 40 to 56 km/h. This is because the metric considers relative forces of the total LCW force.

An upgrade of the metric was developed at the end of the project in order to reflect forces in Row 2. This modified metric could not be tested at different impact speeds except for GCM simulation models. In general this modified metric works similar but it includes a fixed value (70 kN) which probably needs to be revised. Therefore further work is needed in order to confirm or define the fixed value with additional simulations.

6.2 Repeatability and Reproducibility

As agreed in the FIMCAR consortium each test procedure had to fulfil a number of tests to investigate the potential of the repeatability and reproducibility (R&R). By definition, repeatability means that two tests have to be performed at the same lab and reproducibility means that two tests have to be performed at different labs. In total a minimum of three tests with identical cars (two in one test lab, one in another test lab) were defined to be necessary. The whole test procedure and assessment should be repeatable and reproducible. For the full-width barrier test both test procedures, FWRB and FWDB, were checked for their R&R capabilities. This was possible because existing test data from previous projects and other parties (e.g. Japan) were made available.

6.2.1 Analysis of Data from Previous Projects

To investigate the repeatability and reproducibility (R&R) of the proposed test procedures and metrics, different full scale tests from previous projects were collected. The following Table 28 shows the available and useful test data for the **FWDB**.

Table 28: Test data for R&R analysis with the FWDB.

	Vehicle	Lab 1	Lab 2	Lab 3	Lab 4	Comment
1	Opel Astra	TRL	TRL			VC-COMPAT
2	Nissan Micra	TNO (Delft)	TNO (TTAI)			APROSYS
3	Fiat Bravo	FIAT	FIAT	IDIADA	IDIADA*	APROSYS

(* Rear seated dummies in this test)

The Opel Astra tests were performed in the European Project VC-Compat and were made available by TRL. The Nissan Micra tests came from the European project APROSYS and were made available by TNO. These test data could be used for repeatability studies. The test data from the Fiat Bravo could also be used for reproducibility analyses because three tests in two different labs were conducted (for one test at IDIADA a different number of dummies compared to the other three tests was used, the test was therefore neglected). These data came also from APROSYS.

The following Table 29 shows the available and useful test data for the **FWRB**. Although in total five tests were made available (three from the Toyota Corolla and two from the Subaru Stella) the analysis could be just used for repeatability because all tests were conducted in one laboratory. The data was supplied by Japan.

Table 29: Test data for R&R analysis with the FWRB.

Full Width Rigid Barrier			
Vehicle	**Lab 1**	**Lab 2**	**Lab 3**
Toyota Corolla	JARI	JARI	JARI
Subaru Stella R	JARI	JARI	

6.2.1.1 R&R Analyses FWDB Opel Astra

In the following Figure 6.12 the total LCW force is shown for the Opel Astra tests. The peak force in test 1 was 557 kN and in test 2 was 549 kN. The progress of both tests is quite similar and comparable. The energy absorbed was within +/- 5 % of vehicle kinetic energy for both tests.

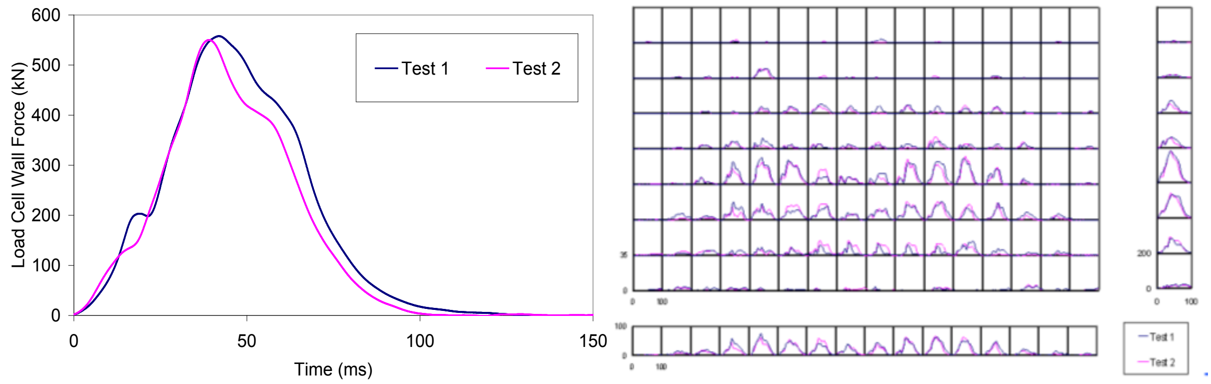


Figure 6.12 Left: Opel Astra R&R tests, total LCW force in kN versus time in ms Right: LCW forces of the individual cell forces.

In Table 30 the values for the modified metric with the Opel Astra data are demonstrated.

As the main output both vehicle passed the FWDB metric.

Table 30 Opel Astra LCW test results with the FWDB metric

Row	**Test 1 Force Value KN up to 40 ms**	**Test 2 Force Value KN up to 40 ms**	**Metric Performance Limits – Test 1 kN**	**Metric Performance Limits – Test 2 kN**
F4	182	179	100	100
F3	127	142	86 (100-14)	77 (100-23)
F4+F3	308	320	200	200
F2	84 (LR =14)	93 (LR = 23)	N/A	N/A
Total	552	550		

6.2.1.2 **R&R Analyses FWDB Nissan Micra**

Two Nissan Micra FWDB tests were performed at TNO in different facilities using the same equipment, one at TTAI in Helmond, one in Delft. The front ride had height differences up to 5 mm and the impact accuracy difference was up to 2 mm in height. In the following Figure 6.13 the forces on the LCW for the Nissan Micra tests are shown. The differences between the vehicles up to 40 ms were 9 kN in Row 3 and 8 kN in Row 4. These numbers indicate already an acceptable repeatability.

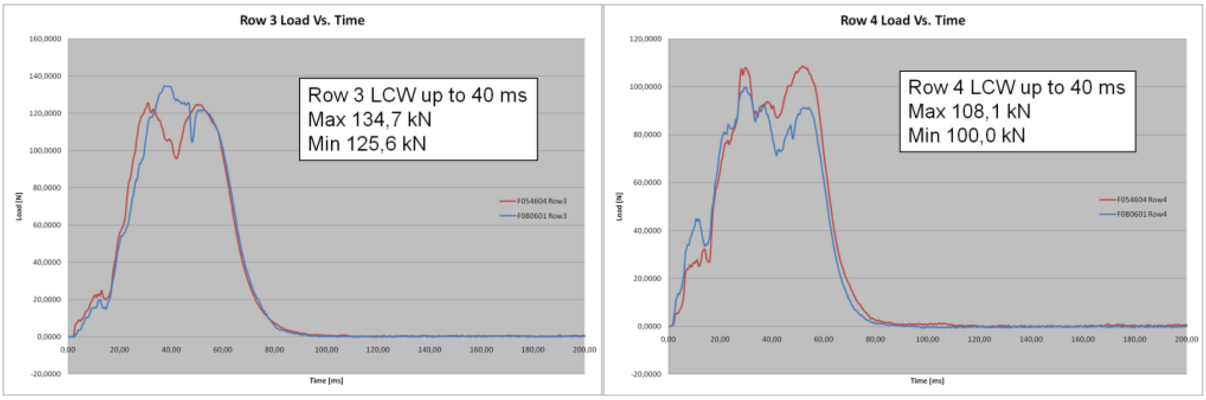


Figure 6.13: Forces on the LCW for Nissan Micra FWDB tests, left: Row 3, right: Row 4.

All tested vehicles passed the different FWDB Metrics.

6.2.1.3 **R&R Analyses FWDB Fiat Bravo**

In total four FWDB tests were performed in the project APROSYS; two at Fiat and two at IDIADA. However, in one test rear seat dummies were used and therefore the test was considered as not being useful for this R&R analyses.

The front ride height differences in these three tests were up to 13 mm and the impact accuracy unknown. In the next Figure 6.14 the LCW forces for the Rows 3 and 4 are shown. The progress of the forces between the two tests performed at FIAT is comparable. However, the Row 3 force of the test at IDIADA is slightly higher and the Row 4 force slightly lower compared to the other two tests.

This difference could be explained by the different height of the vehicles. Pictures from the barrier confirm these findings, although the ride height was not recorded.

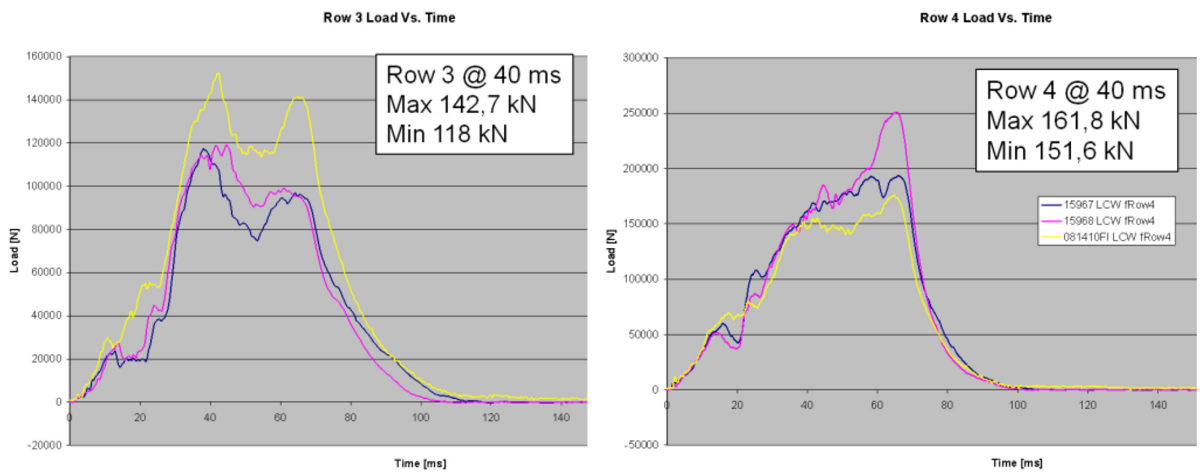


Figure 6.14: Forces on the LCW for Fiat Bravo FWDB tests, left: Row 3, right: Row 4.

The next Figure 6.15 shows the results of the three tests with the first metric for the FWDB. The numbers indicate an acceptable reproducibility.

Method B(1) FWDB: @ 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	FIAT FWDB test 15967		FIAT FWDB test 15968		IDIADA FWDB test 081410FI	
	Value	OK/KO	Value	OK/KO	Value	OK/KO
Time at 400kN (ms)	33.55	NA	33.05	NA	32.15	NA
F3+F4 > 180 kN (kN)	236.2	OK	235.6	OK	224.6	OK
F3 > 85 kN (kN)	97.9	OK	98.5	OK	106.4	OK
F4 > 85 kN (kN)	138.3	OK	137.1	OK	118.2	OK
Global	OK		OK		OK	

Figure 6.15: FIAT Bravo FWDB R&R analysis.

All tested vehicles passed the different FWDB Metrics.

6.2.1.4 R&R Analyses FWRB Subaru Stella

In Japan two Subaru Stella were tested against the FWRB with a test speed of 55 km/h (one in JNCAP, one at JAMA). The difference of the impact point was 10 mm. The forces for Row 3 and 4 are plotted in the next Figure 6.16. The forces and also the characteristics of the forces are very similar for both vehicles.

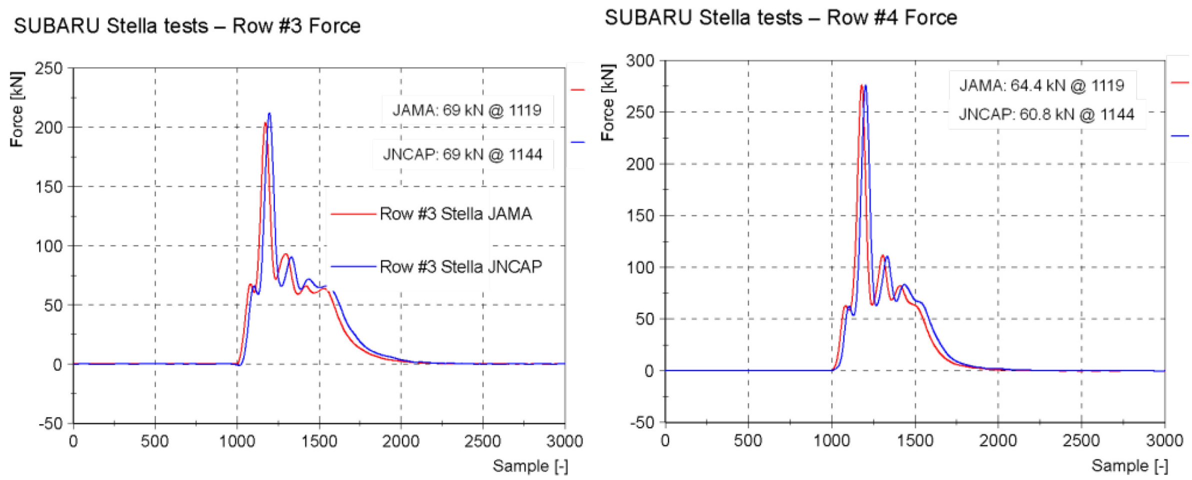


Figure 6.16: Forces on the LCW for Subaru Stella FWRB tests, left: Row 3, right: Row 4

The calculated metric for these vehicles are shown in the next table. Both vehicles would pass the initial metric and also the upgrade metric as they should.

Table 31: Subaru LCW test results with the FWRB metric.

	Current Status			Metric Upgrade				
	F3+F4 [kN]	F4/(F3+F4)	F3+F4>100 0.2<F4/(F3+F4)<0.8	LR=Min [(F2+F1-25 kN); 35 kN]	F4	F3	F4>35 kN	F3>(35 kN-LR)
JAMA	133.4	0.48	PASS	0	64.4	69	PASS	PASS
JNCAP	129.8	0.46	PASS	0	60.8	69	PASS	PASS

It could be stated that in the FWRB tests a good repeatability was seen in the LCW total Force and also for the row forces F1, F2, F3 and F4. The LCW recorded 200 kN before the engine collapsed. The current status and the upgraded FWRB Metric with the limit reduction were passed.

6.2.1.5 **R&R Analyses FWRB Toyota Corolla**

There were R&R test data available also for the Toyota Corolla. This vehicle was tested for JMLIT, JAMA and JNCAP. All vehicles were tested at 55 km/h with the same test weight. The impact point had differences up to 9 mm in the three tests. It should be noted that the undercover was not installed in the tests performed for JMLIT and JAMA.

The Figure 6.17 shows the forces on Row 3 and Row 4 for the Toyota Corolla tests. The forces are very similar up to 200 kN. The engine hits the LCW after the 200 kN. After the engine collapsed differences can be seen in the force characteristics. But some of these differences can also be due to the missing undercover.

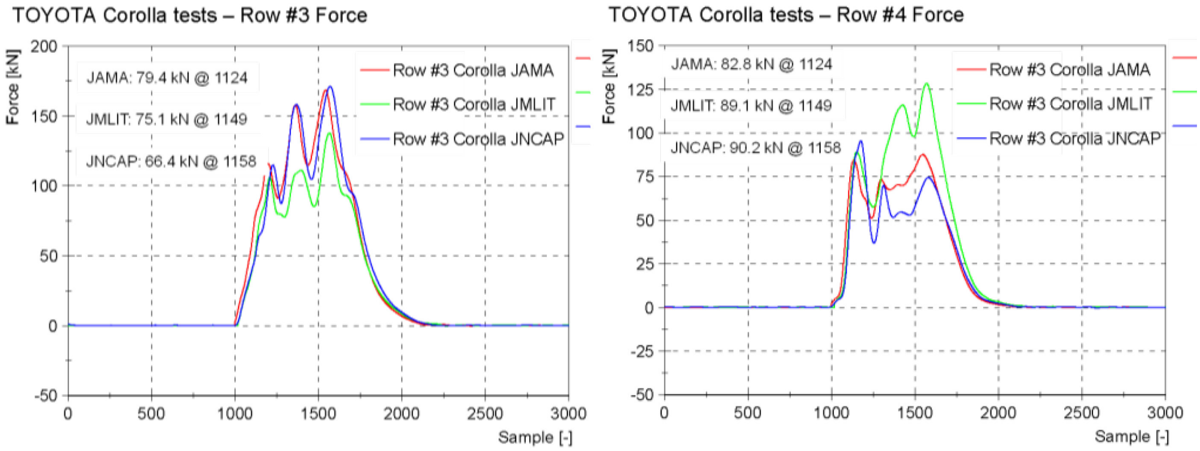


Figure 6.17: Forces on the LCW for Toyota Corolla FWRB tests, left: Row 3, right: Row 4.

The next Table 32 shows the results for the Toyota Corolla and the FWRB metric. All tested vehicles passed as they should. The differences are small and all tested vehicles have enough safety margins to pass in both metrics.

Table 32: Toyota Corolla LCW test results with the FWRB metric

	Current Status			Metric Upgrade				
	F3+F4 [kN]	F4/(F3+F4)	F3+F4>100 0.2<F4/(F3+F4)<0.8	LR=Min [(F2+F1-25 kN); 35 kN]	F4	F3	F4>35 kN	F3>(35 kN-LR)
JAMA	162.2	0.51	PASS	0	82.8	79.4	PASS	PASS
JMLIT	164.2	0.54	PASS	0	89.1	75.1	PASS	PASS
JNCAP	156.6	0.57	PASS	0	90.2	66.4	PASS	PASS

6.2.1.6 **Conclusions FWRB R&R**

The results also indicated that dummy injury for all five tests were below UN-ECE Regulation 94 limits. Good repeatability was observed in the LCW total force, in particular for F1, F3 and F4 up to 200 kN. But a mismatch in F2 for the Toyota Corolla occurred due to components modifications (Undercover effect). The LCW recorded 200 kN before the engine dumps. After the engine collapsed some discrepancies could be seen in row forces F3 and F4.

All tested vehicles passed the different FWRB Metrics.

6.2.2 Analysis of FIMCAR R&R data

To add more test data for the R&R analyses of the FWDB test procedure, three Supermini 1 FWDB tests were performed at different test labs - one at FIAT and two at BASt. The front ride height differences were up to 7 mm and the impact accuracy was up to 2 mm in height.

The LCW forces for Row 3 and Row 4 are shown in Figure 6.18. The maximum forces up to 40 ms had difference up to 23 kN in Row 3 and differences up to 40 kN in Row 4. Surprisingly one test from BASt and one test from FIAT are quite similar, but the second test at BASt showed the differences.

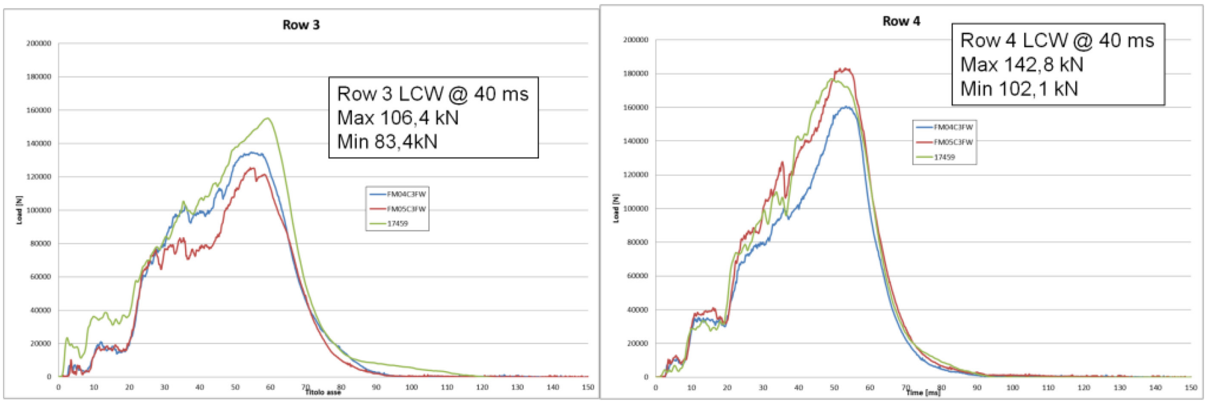


Figure 6.18: Forces on the LCW for Supermini 1 FWDB tests, left: Row 3, right: Row 4.

These differences were remarkably higher as seen in previous R&R analyses. Further examination of the vehicles and the test data showed that the bending of the structure was different. Supermini 1 is a single load path vehicle that already showed instable deformation pattern in car-to-car tests.

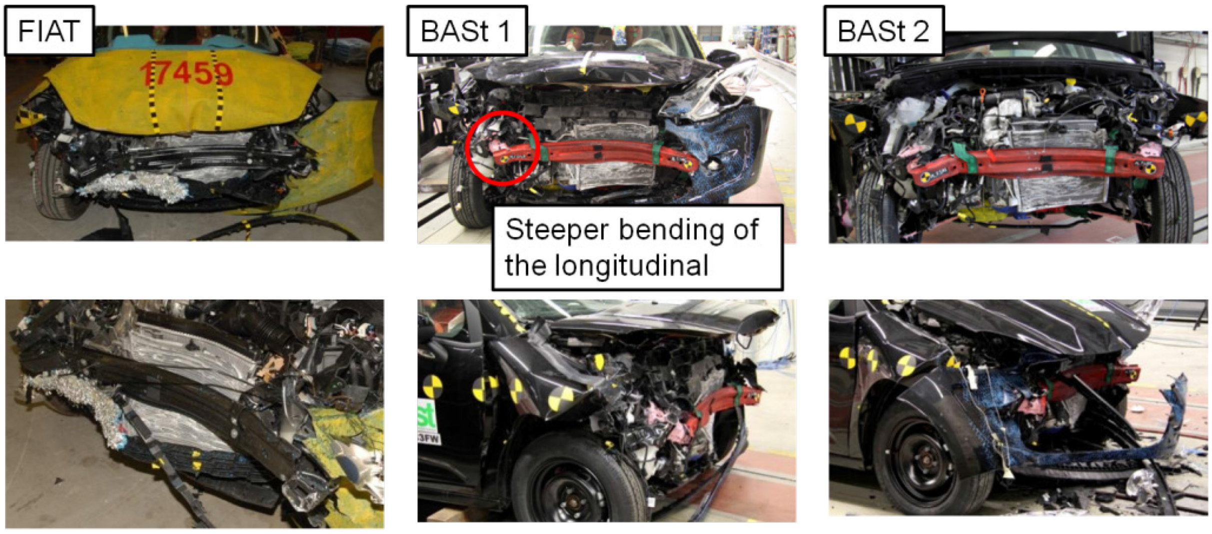


Figure 6.19: Comparison of the three Supermini 1 FWDB tests.

The deformation of the structure could partially explain the discrepancy in the force characteristics. Another explanation for the differences was the LCW used at BASt. This LCW does not fully fulfil the developed FIMCAR specifications that were finalised after scheduling the tests.

In total for the FWDB test procedure five different vehicles were tested at six different test labs. As a main conclusion all vehicles passed the metric as they should. The differences on total LCW force level are usually up to 8% and the differences on row force level were up to 15%. The exception was the Supermini 1 which had higher differences in the row forces. This was explained by different bending of the structures and the unstable rails of this vehicle, which had one load path.

6.2.3 Conclusions

Full scale crash test data analyses from previous projects and Japan were collected to analyse repeatability and reproducibility for both full width test procedures. The analyses indicate that there are reasonable results for both test procedures, the FWRB and the FWDB. However, as a final step to check the proposed test procedures three further tests in different test laboratories were conducted.

The FIMCAR consortium concluded: "Repeatability and Reproducibility is acceptable, in line with other crash tests, for cars with a stable front structure in this test mode. For further analysis of R&R the use of a stable front structure and sum forces above 500 kN is recommended (a good candidate would be Renault Mégane). Furthermore the LCW requirements as developed by FIMCAR shall be met."

6.3 Load Spreading of the Deformable Element

6.3.1 Background

In 2006 as part of the VC-Compat project, component tests were performed to investigate how the deformable barrier affected the loads measured on a Load Cell Wall (LCW) placed behind it in an FWDB test [Davies 2006]. These tests found that:

- The global force was repeatable with the total LCW force, energy and momentum balance all within ±4% of the calculated value
- The differences seen between individual load cells was greater than expected with possible reasons being differences in barrier deformation or bridging between the load cells

It was noted in VC-Compat that further investigation was required to understand better the reasons for the differences seen between individual load cells.

6.3.2 Objectives of Work

Based on the conclusions from VC-Compat the objective of the work was to:

- Determine the reasons for the unexpected differences in peak loads seen between individual load cells

This would be done by performing additional component tests to investigate whether the aluminium backing plate or the interface between the two layers affects distribution of load between cells.

6.3.3 Test Configuration

The testing was performed in the Impact Sled Facility (ISF) at TRL. The testing was the same setup as the testing in VC-Compat. The sled was fitted with a solid flat front plate. The sled impacted a section of aluminium honeycomb with FWDB specification load cells behind it to measure the force. A photograph of the setup is shown in Figure 6.20.

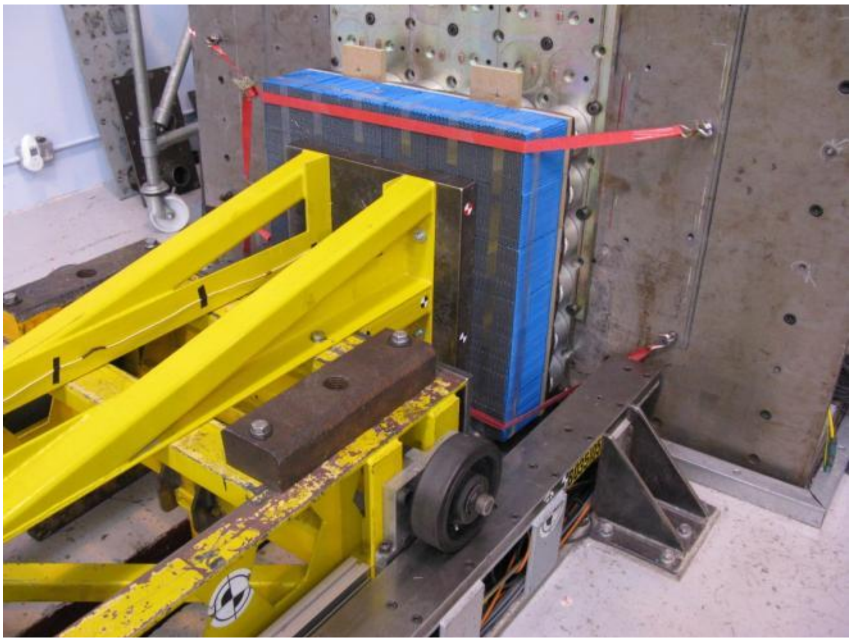


Figure 6.20: Setup of LCW component testing.

The specifications of the testing were:

- Speed: 40 km/h
- Sled mass: 762 kg
- Impactor size: 500 mm x 500 mm
- 6x6 LCW matrix covered by barrier (750 mm x 750 mm)
- Impactor aligned with central 4x4 cells

The LCW was checked for flatness in the horizontal, vertical and diagonal direction and found to be within a tolerance of ±0.5mm in all directions. When the honeycomb barrier was fitted to the wall, the segments of the honeycomb were aligned with the interfaces between the load cells.

6.3.4 Test Matrix

The test matrix for the tests performed in VC-Compat in 2006 and the tests performed in FIMCAR in 2011 are shown in Table 33.

Please note that the standard FWDB construction is as follows:

The deformable element is formed from two layers of aluminium honeycomb, with an overall depth of [300 mm], a minimum height and width of 750 mm and 2000 mm respectively.

The first layer of the deformable element has a crush strength of 0.34 MPa and is 150 mm deep, the second layer has a crush strength of 1.71 MPa and is 150 mm deep. In addition, the second layer is segmented every 125 mm in the horizontal and vertical directions starting at 125 mm from the outer edges. The two layers are joined with a muslin interlayer and there is no cladding on any faces other than the mounting face. The mounting face is clad with a 0.5 mm aluminium sheet which protrudes a set distance 40 mm from the upper and lower faces of the barrier to provide mounting flanges for attachment to the load cell wall.

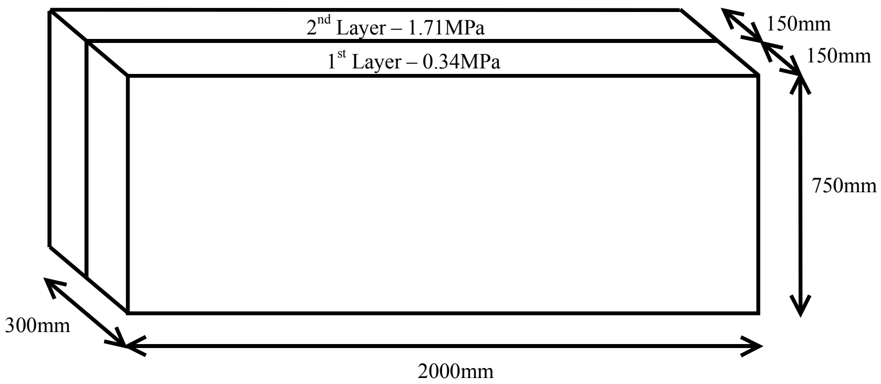


Figure 6.21: Construction of standard Full Width Deformable Barrier.

Table 33: Test matrix of LCW component tests.

2006

Test no.	Barrier	Test speed	Sled mass
1	Standard FWDB	40km/h	762kg
2	Standard FWDB	40km/h	762kg
3	'Optimised' FWDB	40km/h	762kg
4	'Optimised' FWDB	40km/h	762kg

2011

Test no.	Barrier	Test speed	Sled mass
1	Standard FWDB	40km/h	762kg
2	Standard FWDB without backplate	40km/h	762kg
3	Standard FWDB without backplate	40km/h	762kg
4	Rear section of standard FWDB without backplate	40km/h	762kg
5	Rear section of standard FWDB without backplate	40km/h	762kg

The optimisation of the FWDB in 2006 involved:

- ensuring that all the rear layer honeycomb blocks came from the same batch
- performing a cell count for each rear segment to ensure a similar number of complete cells in each block

The reasoning behind the testing in 2011 was:

- To perform a Standard FWDB test to ensure consistency between the tests performed in 2006 and the tests performed in 2011
- To perform tests with the Standard FWDB but without the aluminium backplate to investigate the effect of the backplate
- To perform tests with just the rear 1.71 MPa layer of the Standard FWDB without the backplate to investigate the effect of the interface between the layers

6.3.5 Test results

Total force against time plots for the five tests performed in 2011 and Test 1 performed in 2006 are shown in Figure 6.22.

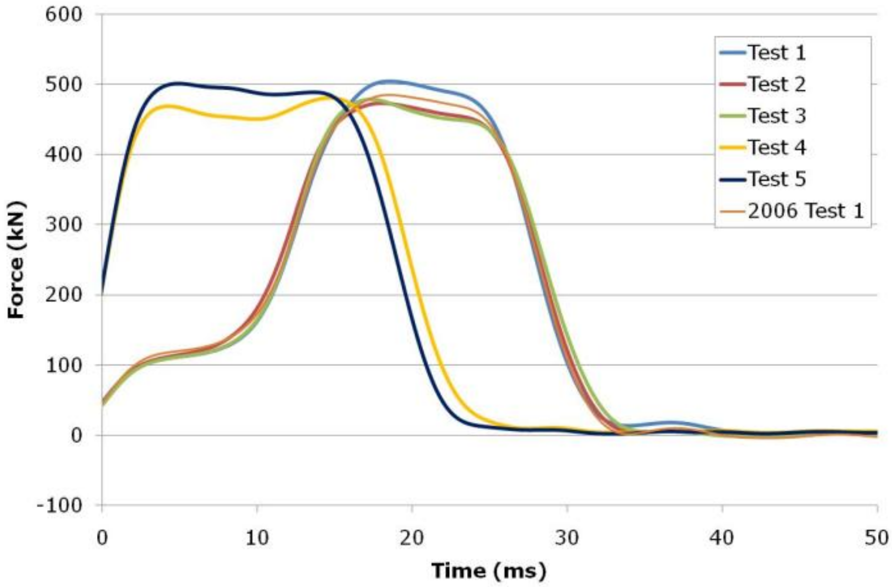


Figure 6.22: Total force against time (CFC60).

The results show a difference of up to 7% in the peak forces in these tests. It is interesting to note that the peak forces recorded were higher than the nominal static crush strength of the honeycomb. The nominal static crush strength of the honeycomb was between 385kN and 427 kN, measured dynamic crush strength approx. 450 to 500 kN. This is likely to be due to factors such as the additional force required to initiate the crush of the honeycomb and trapped air increasing its nominal static crush strength.

Figure 6.23 shows an example of the differences between forces measured by the different load cells in a single test.

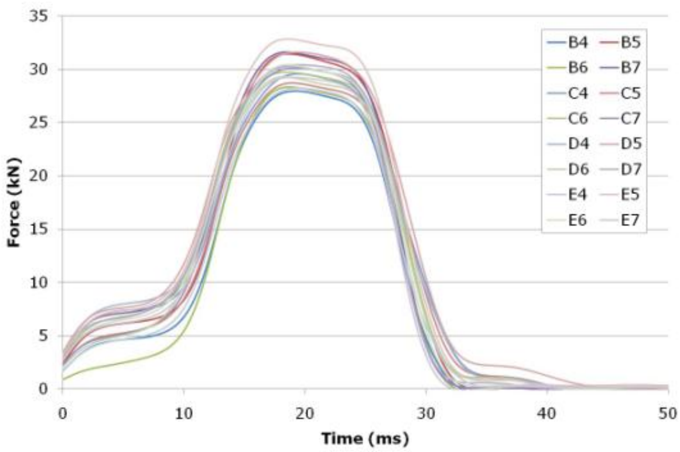


Figure 6.23: Force against time for each Load Cell in Test 1 2011.

The peak forces in each cell for 2011 Test 1 and 2006 Test 2 are shown in Figure 6.24 and Figure 6.25.

0.8	2.0	4.6	1.8	4.0	0.5
1.2	28.0	29.6	30.3	28.2	1.8
0.2	31.5	28.7	31.6	32.9	0.5
2.8	28.4	29.7	29.3	30.4	2.1
0.9	31.6	30.1	30.4	29.3	0.8
0.8	0.7	1.6	0.1	1.9	0.5

29.0
31.2
29.5
30.3

Figure 6.24: Peak cell force in 2011 Test 1 (Standard FWDB) with average centre cell row force.

1.7	2.8	3.9	4.7	1.6	1.2
0.3	25.6	27.0	27.5	25.6	0.5
2.9	30.8	29.2	29.9	29.5	4.4
0.6	27.3	27.5	35.2	28.2	0.3
0.4	28.3	28.4	30.3	31.2	0.1
1.7	2.3	0.3	0.8	1.9	0.2

26.4
29.9
29.6
29.5

Figure 6.25: Peak cell force in 2006 Test 2 (Standard FWDB) with average centre cell row force.

The results show that for the 2011 test the maximum peak cell force was 32.9 kN and the minimum peak cell force was 28.0 kN, giving a difference of 4.9 kN. For the 2006 test the maximum peak cell force was 35.2 kN and the minimum peak cell force was 25.6 kN, giving a difference of 9.6 kN.

The results for the tests without the backplate (2011 Test 2 and Test 3) are shown in Figure 6.26 and Figure 6.27.

0.2	1.9	2.4	1.7	2.1	0.2
0.8	28.2	28.7	28.5	28.2	0.6
0.5	30.6	28.1	29.2	31.1	0.5
1.3	28.7	28.2	27.7	28.2	0.9
0.6	31.0	29.8	29.0	28.6	0.2
0.0	1.1	1.4	0.1	1.2	0.1

28.4
29.8
28.2
29.6

Figure 6.26: Peak cell force in 2011 Test 2 (Standard FWDB without backplate) with average centre cell row force.

0.1	0.8	2.1	0.3	0.8	0.2
1.4	28.6	28.9	28.5	29.5	1.7
0.8	30.0	29.6	28.6	31.0	1.2
1.1	30.2	28.9	27.5	28.5	1.1
1.3	31.7	30.2	30.6	28.4	0.8
0.1	1.0	1.1	0.1	1.4	0.1

28.8
29.8
28.8
30.2

Figure 6.27: Peak cell force in 2011 Test 3 (Standard FWDB without backplate) with average centre cell row force.

For the tests without the backplate, the maximum peak cell differences are 3.4 kN and 3.5 kN respectively, compared to 4.9 kN and 9.6 kN for the Standard FWDB. This shows an improvement in peak cell force distribution. The average row force differences for the tests without the backplate are 1.6k N and 1.4 kN respectively, compared to 1.2 kN for the Standard FWDB. This shows a much smaller change.

The results for the tests without the backplate and with the rear layer of honeycomb only are shown in Figure 6.28 and Figure 6.29.

0.3	1.2	1.3	0.6	0.9	0.4
0.2	29.5	29.6	30.9	32.2	1.1
0.1	30.0	28.5	31.6	29.8	0.7
0.1	31.2	29.2	28.9	30.5	0.7
0.2	30.9	32.6	31.4	28.3	1.4
0.1	0.2	0.2	0.1	0.2	0.2

30.6
30.0
30.0
30.8

Figure 6.28: Peak cell force in 2011 Test 4 (FWDB without backplate, rear layer only) with average centre cell row force.

0.3	0.4	1.2	0.6	0.5	0.4
0.3	31.9	33.0	32.7	31.5	1.7
0.2	33.7	30.8	30.2	31.0	0.8
0.3	31.6	31.6	28.9	28.4	0.8
0.2	34.7	31.3	31.7	28.8	1.5
0.1	0.4	0.4	0.1	1.1	0.1

32.3
31.4
30.1
31.6

Figure 6.29: Peak cell force in 2011 Test 5 (FWDB without backplate, rear layer only) with average centre cell row force.

The results for the tests without the backplate, the maximum peak cell differences are 4.3 kN and 6.3 kN respectively, compared to 4.9 kN and 9.6 kN for the standard FWDB. This shows little consistent change. The average row force differences for the tests without the backplate are 0.8 kN and 2.2 kN respectively, compared to 1.2 kN for the Standard FWDB. This shows little consistent change.

Overall, there is some reduction seen in peak cell force distribution when the effect of the backplate is removed, however when the effect of the interface layer is also removed, the distribution is similar to the Standard FWDB. This may be due to increased instability of the honeycomb when the interface and backplate are removed. Little or no change in the peak row force distribution was seen.

6.3.6 Conclusions

- The causes of the ‘greater than expected’ differences in peak cell forces are still not understood clearly but it is likely to be a combination of factors. However it was found that neither the backplate nor interface layer are major contributors. Other contributors may include tolerance in quasi-static crush, effect of block trimming and interaction between blocks. One possible method to reduce any increase in force caused by crush initiation is to use pre-crushed honeycomb.
- When cell forces are averaged, for example across a row, the differences are reduced greatly, and therefore a metric which does this could possibly be acceptable.
- The total LCW force was found to be reasonably repeatable with differences up to approximately 7%. However the peak cell force was found to have differences of up to 15% in tests with the standard barrier, and up to 27% for the tests performed in 2006. The peak row forces were found to have differences of up to 4% with the standard barrier, and up to 12% for the tests performed in 2006.
- There was some reduction in LCW peak cell force distribution when the effect of the backplate was removed, however when the effect of the interface layer was also removed, the distribution was similar to the Standard FWDB. This may be due to increased instability of the honeycomb when the interface and backplate are removed. Little or no change in the peak row force distribution was seen

7 SUMMARY OF CONCLUSIONS

The objective of work package 3 was to develop a full overlap test procedure. Therefore the set-up of assessment criteria and their validation was needed. Performance criteria for the assessment procedure were defined based on the outcome of the FIMCAR accident analyses and the FIMCAR priorities defined.

In parallel the test and assessment procedure was developed for both configurations, the FWRB and the FWDB. In a later phase of the project the focus was settled on the FWDB test procedure, because the FIMCAR consortium agreed on this.

According to the FIMCAR priorities the main aims of the full width test were:

- Alignment with part 581 zone (initial loading is evaluated above and below the centreline)
- Not discourage a load path in alignment with Load Cell Wall Row 1 and 2 and possibly encourage

These priorities were set because structural alignment is one main pillar of compatibility. It also helps to prevent under and override which was seen in accident analyses. And it also supports the establishment of a common interaction zone.

As a result following conclusions can be made for the full width test procedure:

1. The full width test shall be performed with a deformable barrier and an LCW to measure force distribution with a test speed of 50 km/h. The full width test and assessment protocol is included in Annex C.

FWDB metric

The proposed metric with Limit Reduction which was developed based on test data with a test speed of 56 km/h, addresses the FIMCAR priorities (structural alignment in part 581 zone and encouragement of load path in alignment with Row 2) and is a good principle. However, further validation of the proposed performance limits is recommended, in particular consideration of light cars and the influence coming from the proposed change in test speed to 50 km/h is needed.

The current metric and associated performance limits which was validated for a test speed of 56 km/h is as follows

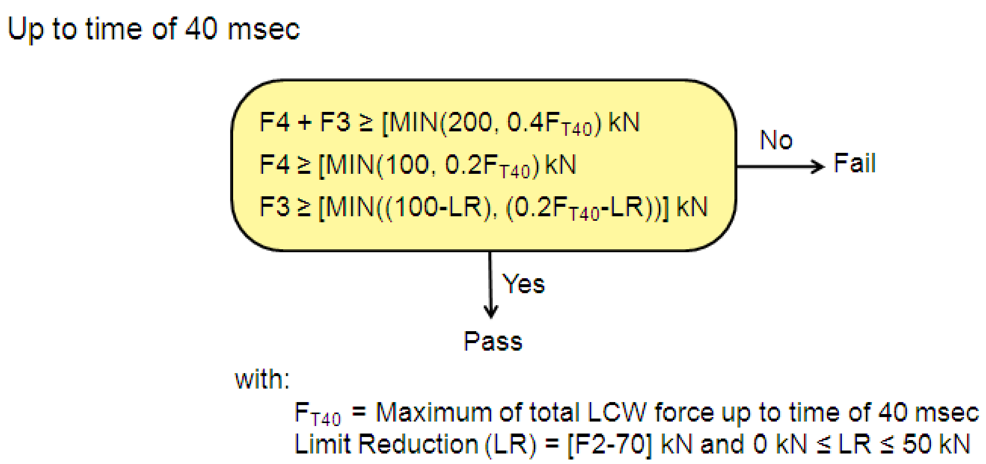


Figure 7.1: FIMCAR FWDB metric.

Lower Load Path

The tests and simulations conducted in FIMCAR indicate that structural alignment is a high priority for frontal impact and compatibility and that vertical load spreading is an important supporting characteristic. In all cases, vehicles with vertical load spreading can be detected with the FWDB if the structures are less than 400 mm behind the bumper. Lower load paths that are detected in a FWDB by exerting more than 70 kN (in the 56 km/h test case) show a benefit for car-to-car crash performance. An FWDB metric that rewards vehicles with 70 kN in Rows 2&3 would be beneficial for vehicle safety.

Over Ride Barrier

To pass the ORB test does not guarantee that the car performs well in car-to-car impacts. The FWDB is detecting structures which have a benefit in car-to-car impacts.

Test Speed

It was important to establish a test severity for the full width test procedures to ensure the candidate procedures were representative of the real world conditions. The real world data indicates that the highest risks for MAIS2+ injuries are in the range 4 to 57 km/h and that this impact severity should be used to direct future car designs. Given that a full width test delta-v usually involves a rebound velocity of approximately 10% the impact speed, a test speed of 50 km/h was selected for a full width test severity, regardless of the barrier face selected.

With all FIMCAR car models it could be shown that the metric works for test speeds in a range from 40 to 56 km/h. This is because the metric considers forces relative to the total LCW force for many vehicles. An upgrade of the metric was developed at the end of the project in order to reflect forces in Row 2. This modified metric could not be tested at different impact speeds yet. In general this modified metric works similar but it includes a fixed value (70 kN) which needs to be revised. Therefore further work is needed in order to confirm or define the fixed value with additional simulations, if the test speed of 50 km/h will be set.

Repeatability & Reproducibility

Full scale crash test data analyses from previous projects and Japan have been collected to analyse repeatability and reproducibility for both full width test procedures. The analyses indicate that there are reasonable results for both test procedures, the FWRB and the FWDB. However, as a final step to check the proposed test procedures three further tests in different test laboratories were conducted and analysed.

Based on this test data repeatability and reproducibility is acceptable, in line with other crash tests, for cars with a stable front structure in this test mode. For further analysis of R&R the use of a stable front structure and sum forces above 500 kN is recommended (a good candidate would be Renault Mégane). Furthermore the LCW requirements as developed by FIMCAR shall be met.

LCW Certification

As part of FIMCAR a Load Cell Wall (LCW) certification procedure was defined. The procedure consists of the LCW definition and certification requirements in terms of wall flatness. In addition a specification and calibration protocol was prepared for the transducers.

Parameter values for both documents were obtained from measurements and analyses on load cell walls and transducers itself. Certification requirements for the wall flatness were based on measurements of three existing walls and an analysis of a trolley test done by BASt. A series of load cells was tested to check and refine values set for non-linearity and hysteresis.

Load spreading of the deformable element

When cell forces are averaged, for example across a row, the differences are reduced greatly, and therefore a metric which does this could be acceptable.

8 ACKNOWLEDGEMENTS

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JAMA supported the FIMCAR project with three additional FWDB tests and test data .

The development of the load cell certification and calibration procedure was supported by Kistler.

Members of the FIMCAR project thank gratefully JMLIT, Nagoya University, JAMA and Kistler for their contributions.

9 GLOSSARY

APROSYS	Integrated Project on Advanced Protection Systems APROSYS was supported in the 6th European Framework Programme
AIS	Abbreviated Injury Scale
ATD:	Anthropomorphic Test Device (crash test dummy)
CIZ:	Common Interaction Zone
ECE	Economic Commission for Europe
EEVC	European Enhanced Vehicle-safety Commission
FIMCAR	Frontal Impact and Compatibility Assessment Research
FWDB	Full Width Deformable Barrier
FWRB	Full Width Rigid Barrier
GRSP	Working Party on Passive Safety
LCW	Load Cell Wall
LTV	Light Truck Vehicle
MAIS	Maximum Abbreviated Injury Scale
MDB	Movable Deformable Barrier
NCAP	New Car Assessment Programme
PEAS	Primary Energy Absorbed Structure
RTD	Research and Technology Development
R&R	Repeatability and Reproducibility
SEAS	Secondary Energy Absorbed Structure
SUV	Sport Utility Vehicle
VC-COMPAT	Vehicle Crash Compatibility VC-Compat was a project funded under the GROWTH programme of the European Commission.
WG15	Workgroup 15 in the EEVC

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ANNEX A: LOAD CELL SPECIFICATION AND CALIBRATION

1. Objective and scope

   The present guideline is general applicable for force measurements with load cells used in the application of a high resolution barrier for frontal vehicle crash testing. It is used to characterise the minimum specifications for the load cell, the calibration procedure and the estimated relative measuring uncertainty of calibration.

   The guideline applies to stepwise (static) and continuous (quasi-static) loading cases during the process of calibration. In the former case, the stepwise calibration, a pure static loading will be applied. At this suitable load periods for each load step have to be sustained in order to provide for creeping effects of the unit under test. In the latter case, continuous calibration, the unit under test will be subjected to a continuously changing load. The load change during calibration has to be chosen in such a way that an adverse calibration effect by dynamic effects is precluded.

   Due to the fact that the choice of calibration procedure, the exposure time and/or the rate of loading depends largely upon the force load device used for the calibration, the user of this guideline, who will be in authority of the calibration, is in charge of the suitable calibration settings.

2. Normative references

   The following normative documents contain provisions which are referred to in this text. In case of any future amendments the possibility of applying the most recent editions of the normative documents should be investigated.

ISO 376:2004	Metallic materials - Calibration of force-proving instruments used for the verification of uniaxial testing machines[1].
ISO 2041:1990	Vibrational shock - Vocabulary.
ISO 6487:2002	Road vehicles - Measurement techniques in impact tests - Instrumentation.
ISO/IEC Guide 98-3:2008	Uncertainty of measurement – Part 3: Guide to expression of uncertainty in measurement (GUM:1995)
SAE J2570:2009	Performance Specifications for Anthropomorphic Test Device Transducers.
SAE J211:2007	Instrumentation for impact tests - Part 1: Electronic instrumentation.

3. Terms and definitions

   3.1. Load Cell Definitions

1. A new version of DIN EN ISO 376 was expected to be published end 2011 but is not available yet. Publication should be monitored and when available reference to updated version included in this document.

3.1.1. Certification

Formal procedure by which an accredited or authorized person or agency assesses and verifies (and attests in writing by issuing a certificate) the attributes, characteristics, quality, qualification, or status of a measurement device or system, in accordance with established requirements or standards.

3.1.2. Calibration

Operation that, under specific conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.

NOTE 1 A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

NOTE 2 Calibration should not be confused with adjustment of a measuring system, often mistakenly called “self-calibration”, nor with verification of calibration.

NOTE 3 Often, the first step alone in the above definition is perceived as being calibration.

3.1.3. Data Channel

All of the instrumentation from and including a single transducer up to and including any analysis procedures that may alter the frequency content or the amplitude content or timing of data. It also includes all cabling and interconnections.

3.1.4. Full Scale Capacity

Full scale capacity is the maximum usable linear range of a data channel.

3.1.5. Non-Linearity (% of full scale capacity)

Linearity is defined as the closeness of the calibration curve to a specified line (source: ANSI/ISA-S37.1). Non-linearity represents the maximum deviation between ideal and actual output signal characteristics in relation to the reference in a specific measuring range. It is expressed in percentage of the range of measurement signal (full scale output).

3.1.6. Hysteresis (% of full scale capacity)

The maximum deviation between ascending and descending output readings taken at the same load point, expressed as a percentage of full scale capacity.

3.1.7. Free Air Resonance

The frequency at which a transducer resonates, when suspended freely in air by a single wire and impacted with a hard surfaced body. This test shall be done while monitoring the channel output to insure each channel’s fundamental output frequency shall be equal to or greater than the specified frequency.

3.1.8. Shear Load Sensitivity (Crosstalk)

One channel of a load cell loaded to a set loading, and the other channel(s) unloaded, the output of the unloaded channel(s) is expressed as a percentage specified of the unloaded channels full scale capacity.

3.1.9. Off-Centre Loading Error
When a force channel is loaded at a distance from the neutral axis, the error in the force channel output with respect to the output when calibrated on the neutral axis is reported as a percentage error of full scale.

3.1.10. Compensated Temperature Range
The range of temperature over which the transducer is compensated to maintain output and zero balance within specified limits.

4. Transducer Specifications

4.1. General Specifications

4.1.1. Transducer Type
Uniaxial force measurement in compression mode (x-axis).

4.1.2. Physical Dimensions
The physical dimensions of contact surface shall be nom. 125 x 125mm minus a clearance in between load cells to avoid interference between proximate transducers.

4.2. Measurement Performance Specifications for Uniaxial Loadcell

4.2.1. Full scale capacity ≥ 300 kN

4.2.2. Overload capacity ≥ 400 kN

4.2.3. Non-Linearity (% of full scale capacity [absolute value]) ≤ 1.0%.

4.2.4. Hysteresis (% of full scale capacity [absolute value]) ≤ 2.0%.

4.2.5. Free Air Resonance ≥ 5kHz [2]

4.2.6. Shear Load Sensitivity ≤ 3% under the loading condition of 50 kN for cross axis channel(s)

4.2.7. Off-Centre Loading Error ≤ 3%2

4.2.8. Temperature Range: 15°C to 30°C

5. Characteristic of the force measuring chain

5.1. Description of the force measuring chain

The force measuring chain comprises of all components from the unit under test / working standard to the indicating output instrument.

The selection and settings of all signal running components, e.g. measuring amplifier and indicating instruments, in the measuring chain of the working standard as well as the unit under test will be left to the user who will be in authority of the calibration. The characteristic function for the transfer behaviour of the signal running components has to be known and the same filter parameters have to be assured. The exchange of the signal running components by an identical component will be permitted to do as long as its systematic error of output value, due to its technical specification and the measuring uncertainty, do not have an essential influence on the calibration result.

All components of the force measuring chain (including connection cables) have to be labelled in particular and precisely.

5.2. Application of Force

[2] Final value could not be set on the basis of FIMCAR testing. For the free air resonance a value of either 4 or 5kHz was proposed. Also for the off-centre loading error a value of either 2% or 3% was proposed. Further studies are needed to set a final value for both parameters. For the time being the less strict values are listed the performance specifications.

All calibration fixtures used for calibration have to be considered as integral part of the unit under test.

5.2.1. Working Standard: Assembly following DIN EN ISO 376
5.2.2. Unit under test: To the greatest possible extent like in the field.

For the calibration with a one component force loading machine a calibration fixture with a three-sided loading base will be used for mounting of the unit under test. The position of the calibration fixture with the unit under test has to be permuted depending on each designated direction of force application (axial or transversal loads).

In the case of a three component force loading machine the unit under test will be mounted by a calibration fixture in one position in order to apply the three forces in each direction.

The application of force will be carried out by the use of a loading head, an example of which is shown in Figure A.1.

I. If the calibration force shall be applied by a 1” steel ball “sphere” a case-hardened loading head with ball joint loading points on all three sides has to be used.
II. If the calibration force shall be applied by a spherical steel stamp a plane loading head has to be used. Dependent on the geometry of the spherical steel stamp and the resultant stress in the contact area it could be necessary to use case-hardened steel plates at the stamp joint loading points

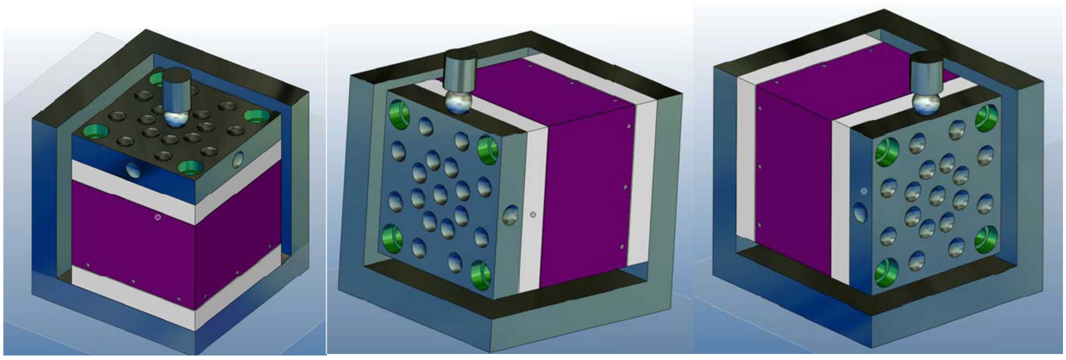


Figure A.1: Loading head with application in axial loading, cross talk Fy and cross talk Fz applications

6. Calibration of the force measuring chain
   6.1. General requirements

The calibration is done by the application of a known force into the force measuring chain. The application of force has to be done by use of a simple force load machine which is equipped with a calibrated working standard. Both the working standard – reference channel - and the unit under test are loaded at the same time. The output of the working standard as well as the unit under test has to be recorded. The measured output of the unit under test is then compared with that of the working standard.

   6.2. Calibration preparation

6.2.1.Reference and display equipment

The adjustments of the reference and display equipment must be carried out as stated in the instruction manual. For the documentation all serial numbers of the reference equipment and all variable settings must be recorded. In addition the relevant parameters of the calibration sequence have to be documented.

6.2.2.Warm-up

The unit under test must be allowed to warm-up prior to calibration. It is thus required to apply the specified supply voltage to the overall measurement chain in order to avoid warming-up errors.

6.2.3.Ambient conditions

At the beginning of the calibration the relevant ambient conditions have to be documented. The ambient temperature must be held steady within +/- 2 °C with respect to a reference temperature of 21°C.

6.3. Calibration process

The manufacturer of load cells should specify the following properties of the cells in data sheets.

6.3.1. Preloading

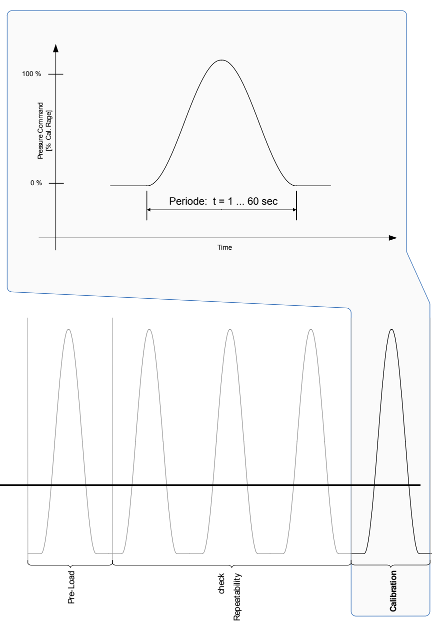
After assembly, the unit under test must be preloaded twice prior to calibration to the final value of calibration load.

6.3.2.Calibration procedure

The method applied for calibration is either a

- ⇨ Stepwise (static) procedure: The output of the unit under test is compared with that of the working standard, while discrete force values are applied from 0 to full scale and back (typical for calibration units with lever-mass system), or a
- ⇨ Continuous (quasi-static) procedure: The output of the unit under test is compared with that of the working standard, while continuously ramping the load from 0 to full scale and back (preferred procedure for piezoelectric sensors).

In case of a stepwise calibration a series of measurements in ascending order and a series of measurements in descending order is performed after the two preload cycles. A minimum of five (5) steps / force levels from zero to the final value of calibration load (FSO) have to be taken for each series. Preferably 20%, 40%, 60%, 80% and 100% of the upper limit of the effective calibration range (FSO).



In case of a continuous calibration a force progression cycle in the shape of a ramp functions with increasing and decreasing load is indicated. As the upper limit of the effective calibration range (FSO) cannot be approached definitely during the loading cycle, it is permitted to marginally exceed the upper limit of full scale calibration range.

For the acquisition of calibration data the pair of readings from the unit under test and the working standard – reference force – might be recorded time-discrete or value-discrete. The time-discrete acquisition will be done by a predetermined sampling rate. The value-discrete data acquisition will record the pairs of readings at specified load values.

6.3.3. Determination of characteristic values

Sensitivity, Non-linearity and Cross-talk are to be determined during calibration on an annual basis and in case of overloading of the transducer.

6.3.3.1. Data evaluation and interpretation

For the evaluation and interpretation of the calibration data the minimum method may be applied. In doing so the zero point of the measured characteristic line will be matched with the zero point of best fit straight line. Subsequently the slope of best fit straight line will be chosen in such a way that the deviation from the measured characteristic line meets a minimisation principle. For the minimisation principle following methods might be used:

- ⇨ The method of "least squares" that assumes that the best-fit curve of a given type is the curve through zero that has the minimal sum of the deviations squared (least square error) from a given set of measurement readings.
- ⇨ The method of "best straight line" (according to ANSI/ISA S37.1-1975) that assumes that the best-fit curve of a given type is the curve through zero that will minimize the maximum of the deviations from a given set of measurement readings.

In order to ensure the comparability of calibration results, it is necessary to declare and to document the method that was used to determine the characteristic calibration values.

The evaluation of the calibration results can be visualized in a so call difference curve by plotting the output signals of the unit under test (load cell) against the reference. The following parameters are calculated.

6.3.3.2. Sensitivity

Change in the response of a unit under test divided by the corresponding change in the value of the reference. The sensitivity is, e.g. defined as the slope of a so called Best Straight Line (BSL) through the calibration curve. The BSL is a line midway the two parallel straight lines closest together and enclosing all output versus reference values on a calibration curve. In addition, it must pass through the zero point based on the assumption that zero reference results in zero output signal.

The force application in the mean axis of the unit under test will be carried out centrically in such a way as described in detail by chapter 6.3.2.

6.3.3.3. Non-linearity

The maximum deviation of a transducer output reading from the ideal output expressed as a percentage of full scale capacity.

The ideal sensor output may be obtained by the terminal line method defined as a straight line connecting a transducer zero load reading and its full scale reading or by alternatives like the Gauss Algorithm meaning the method of least squares.

6.3.3.4. CrossTalk

Crosstalk is based on output measured in the e.g. X-direction while respectively applying a load up to 50 kN to the perpendicular Y- and Z-directions of the unit under test. With one channel of a load cell, loaded to capacity and the other channel unloaded, the output of the unloaded channel may be expressed as:

- A percentage of the unloaded channel's full scale capacity

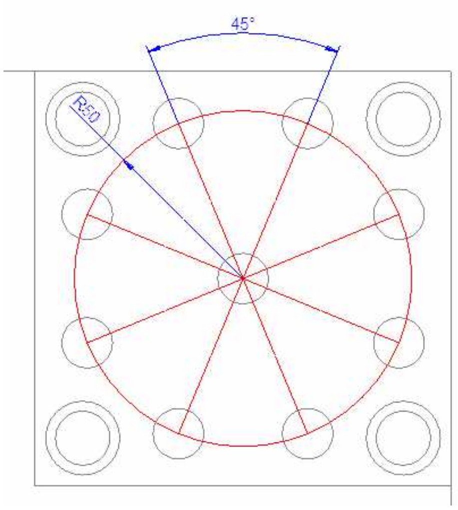
or

- A percentage of the loaded channel's full scale capacity.

or

- A percentage of the loaded channel's full scale calibration range (50 kN).

In order to ensure the comparability of calibration results, it is necessary to declare and to document the method that was used to determine the crosstalk values.



6.3.4. Determination of extended values

Extended values relate to off-centre loading error, hysteresis and free air resonance. These data are to as design verification and to be collected once per load cell design.

6.3.4.1. Off-Centre Loading Error

The off-centre loading error may be determined by applying forces in the axial direction at various eccentric application points. The area for admissible off-centre force application should be on a radius of 50 mm around the centre axis with 45° inclination between and, if possible, in the four corners of the unit under test. Maximum load should be the upper limit of the effective calibration range (FSO). The sensitivity deviation has to be calculated for each force application point and the maximum deviation shall be used to determined the maximum off-centre loading error.

Note: The identification of the off-centre loading error should be only considered as a type evaluation process. In particular a ratio of 1 to 25 units shall be considered.

6.3.4.2. Hysteresis

As defined in 3.1.6.

6.3.4.3. Free air resonance

The free air resonance may be determined by suspending the transducer freely by a single wire and impacting in the loading direction by a modal hammer. Channel output will be monitored to insure each channel's fundamental output frequency shall be equal to or greater than the specified frequency. Anti Aliasing filters and sample frequency should be chosen such to avoid Aliasing effects (see SAE J2011)

7. Classification

The calibration according to this guideline does not provide for classification.

8. Calibration Certificate

Will a calibration be executed and at that time the force measuring chain is in compliance with the requirements of this guideline, the calibration laboratory will draw up a calibration certificate with at least the following information:

- Calibration laboratory and responsible person,
- Date of the calibration,
- Specification of the calibration method and operation sequence,
- Information of the used measurement standards,
- Ambient conditions at which the calibration was performed,
- Result of calibration,
- Identification of any limit violation,
- Tabulation and/or graphical representation of the calibration results,
- Approximation function (e.g. linear equation) and its method of determination.
- Identification number of the calibration certificate, number of pages

ANNEX B: LOAD CELL WALL SPECIFICATION AND CERTIFICATION

2. Objective and scope

   The present guideline is general applicable for a high resolution load cell wall used in frontal vehicle compatibility assessment. It is used to characterise the minimum specifications for the load cell wall and its certification.

3. Specifications

   3.1. General Specifications

   3.1.1. Physical Dimensions and positioning

   The physical dimensions of the load cell wall shall be nom. 1000 x 2000mm. The ground clearance defining the height of the load cell wall above the ground shall be 80 ±2 mm.

   3.1.2. Transducer dimensions

   The physical dimensions of contact surface of the load cells used in the wall shall be nom. 125 x 125mm minus a clearance in between load cells to avoid interference between proximate transducers.

   3.1.3. Wall flatness

   3.1.3.1. Alignment of transducer centre

   Transducers shall be positioned such that centre point locations of adjacent cells are aligned to have a depth variation (measured perpendicular to load cell wall) of 1 mm or less.

   3.1.3.2. Alignment of transducer corners and edges

   Transducers shall be positioned such that corners and edges of adjacent cells are aligned to have a depth variation (measured perpendicular to load cell wall) of 1 mm or less.

   3.1.4. Transducer numbering

   The transducers shall be positioned in a square grid. The numbering indication of the transducers shall be according to Figure B.1. The numbering sequence of transducers in a column starts at 01 for the lowest cell. The numbering sequence in a row starts at 01 at the left side (facing towards the barrier). A transducer number consist of its number in the column followed by its number in the row.

   3.2. Measurement performance specifications

   3.2.1. Sampling rate ≥ 10 kHz

   3.2.2. Transducer specifications and calibrations as included in Annex A

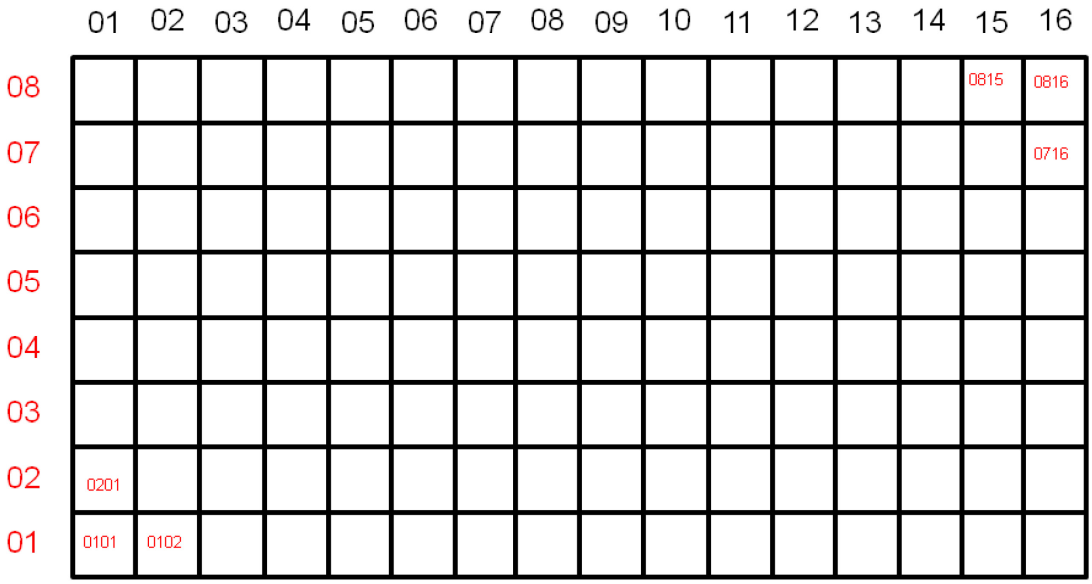


Figure B.1: Load cell numbering

4. Certification
   4.1. General requirements

The certification is done by measuring the position at the centre and the corners of each transducer in a 3-Dimensional space. This has to be done by use of an adequate measuring device that has sufficient range to provide data for all transducers in the wall. Data shall be provided in metric units.

The measurement has to be done directly on the transducers. Protective layers like wooden plates have to be removed.

   4.2. Position measurement
      4.2.1. If applicable remove the wooden cover plates from the transducers.
      4.2.2. Setup the Faro arm or alternative measurement device. If possible position the Faro arm in such a position that no frog leaps are necessary.
      4.2.3. Measure on each transducer the position of the centre and corner points. For the corners measurements should be taken 5 mm from each side. See Figure B.2.
      4.2.4. In case the indicated position is not applicable, for example if there is a threaded hole, take an appropriate position as close a possible.

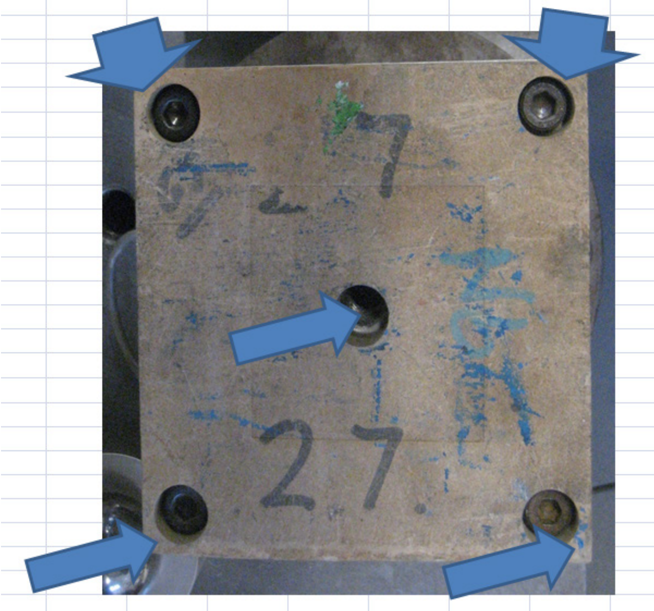


Figure B.2: Measurement locations

4.3. Determination of wall flatness

4.3.1. A reference for the transducer position in the direction perpendicular to the wall (X direction in Figure B.3) is set by summing measured positions in this direction for all transducers at centre point location. An average depth position is obtained by dividing the sum by the number of transducers.

4.3.2. Calculate depth positions (X direction in Figure B.3) for corner and centre point positions by subtracting the average depth position from the measured position in the direction perpendicular to the wall.

4.3.3. Calculate the difference of depth position between transducer centres of all adjacent cells (column wise, row wise and diagonal wise). The resulting value should meet specifications set in 2.1.3.1.

4.3.4. Calculate the difference of depth position between all adjacent transducer corners (column wise, row wise and diagonal wise). The resulting value should meet specifications set in 2.1.3.2.

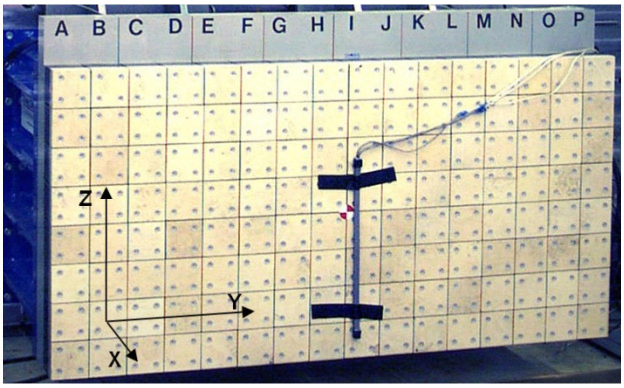


Figure B.3: Measurement locations

ANNEX C: FULL WIDTH TEST AND ASSESSMENT PROTOCOL

Table of Contents

This document describes the draft test protocol for the Full Width Deformable Barrier (FWDB) test. It must be noted that some aspects of the test protocol have yet to be defined. In such cases options have been defined, which are identified using square brackets. The main options are:

- Additional instrumentation (accelerometers) to fully evaluate compatibility for the FIMCAR project

Please note that for the tests to be performed in the FIMCAR project the high resolution Load Cell Wall (LCW) and additional instrumentation to fully evaluate compatibility should be included in all tests.

Much of the protocol is similar to the Euro NCAP v4.1 frontal impact test protocol. Those familiar with the Euro NCAP protocol should note that the main differences are in the following sections:

1.5 Suspension setting

1.6 Normal ride height

2.3.1 Optional intrusion measurements

4.2 Vehicle instrumentation – accelerometers, airbag current clamps, etc.

4.3 Load Cell Wall (LCW)

5.0 Camera Locations

9.0 Speed / Barrier Alignment / Impact Accuracy vertical

10.0 Calculation of injury parameters – additional parameters such as HIC15, Nij, etc.

11.0 Deformable Barrier specification

1 VEHICLE PREPARATION

1.1 Unladen Kerb Mass

1.1.1 The capacity of the fuel tank will be specified in the manufacturer's booklet. This volume will be referred to throughout as the "fuel tank capacity"

1.1.2 Syphon most of the fuel from the tank and then run the car until it has run out of fuel.

1.1.3 Calculate the mass of the fuel tank capacity using a density for petrol of 0.745g/ml or 0.840g/ml for diesel. Record this figure in the test details.

1.1.4 Put water, or other ballast, to this mass in the fuel tank.

1.1.5 Check the oil level and top up to its maximum level if necessary. Similarly, top up the levels of all other fluids to their maximum levels if necessary.

1.1.6 Ensure that the vehicle has its spare wheel on board along with any tools supplied with the vehicle. Nothing else should be in the car.

1.1.7 Ensure that all tyres are inflated according to the manufacturer's instructions for half load.

1.1.8 Measure the front and rear axle weights and determine the total weight of the vehicle. The total weight is the "unladen kerb mass" of the vehicle. Record this mass in the test details.

1.1.9 Measure and record the ride heights of the vehicle at all four wheels.

1.2 Reference Loads

1.2.1 Calculate 10 percent of the fuel tank capacity mass as determined in 1.13

1.2.2 Remove this mass of ballast from the fuel tank, leaving 90 percent of the mass in the tank.

1.2.3 Place both front seats in their mid-positions. If there is no notch at this position, set the seat in the nearest notch rearward (this will be done more completely in section 6).

1.2.4 Place a mass equivalent to the 50th%ile driver test dummy (including instrumentation and cables) and a 5th%ile passenger test dummy on the front seats.

1.2.5 Place 36kg in the luggage compartment of the vehicle. The normal luggage compartment should be used i.e. rear seats should not be folded to increase the luggage capacity. Spread the weights as evenly as possible over the base of the luggage compartment. If the weights cannot be evenly distributed, concentrate weights towards the centre of the compartment.

1.2.6 Roll the vehicle back and forth to “settle” the tyres and suspension with extra weight on board. Weight the front and rear axle weights of the vehicle. These loads are the “axle reference loads” and the total weight.

1.2.7 Record the axle reference loads and reference mass in the test details.

1.2.8 Record the ride heights of the vehicle at the point of the wheel arch in the same transverse plane as the wheel centres. Do this for all four wheels.

1.2.9 Remove the weights from the luggage compartment and the front and rear seats.

1.3 Vehicle width and Overlap

1.3.1 Determine the centreline of the vehicle. Mark a line along the centreline of the vehicle. This line will align with the vertical centreline of the load cell wall.

1.4 Vehicle Preparation

Care should be taken during the vehicle preparation that the ignition is not switched on with the battery or airbag disconnected. This will result in an airbag warning light coming on and the airbag system will need to be reset. The manufacturer will need to be contacted if this occurs.

1.4.1 Ensure that live battery is connected, if possible in its standard position and that the driver airbag is connected. Check that the dashboard light for the airbag circuit functions as normal. The vehicle battery may be replaced with a dummy unit and live battery placed in the luggage compartment of the vehicle. This action is at the test labs discretion, but the manufacturer must be consulted to ascertain if this is likely to cause problems with any of the vehicle's systems.

1.4.2 In the event that the engine fluids are to be drained then drain the coolant, oil, air-conditioning (air conditioning fluid, and replace with an equivalent weight of water or other ballast).

1.4.3 If the fluids are drained then measure the weights of each of these fluids, excluding the air conditioning fluid, and replace with an equivalent weight of water or other ballast.

1.4.4 Remove the luggage area carpeting, spare wheel, and any tools or jack from the car. The spare wheel should only be removed if it will not affect the crash performance of the vehicle.

1.4.5 An emergency abort braking system may be fitted to the vehicle. This is optional; the test facility may elect to test without an abort system. Where such a system is fitted its inclusion shall not influence the operation or function of any of the foot controls, in particular the brake pedal. The position and resistance to the movement of the pedals shall be the same prior to fitment of the system. Remove as little as possible of the interior trim; any mass compensation will be made when all equipment has been fitted.

1.4.6 Fit the on-board data acquisition equipment in the boot of the car. Also fit any associated cables, cabling boxes and power sources.

1.4.7 Place a weights equivalent to the 50%ile driver test dummy (including instrumentation and cables) on each of the front seats (with the seats in their mid positions).

1.4.8 Weigh the front and rear axle weights of the vehicle. Compare these weights with those determined in section 1.2.6

1.4.9 If the axle weights differ from those measured in 1.2.6 by more than 5% (of the axle reference loads) or by more than 20 kg, remove or add items which do not influence the structural crash performance of the vehicle. Similarly, if the total vehicle mass differs by more than 25 kg from the reference mass, non-structural items may be removed or added. The levels of ballast in the fuel tank (equivalent in mass to 90% capacity fuel) may also be adjusted to help achieve the desired axle weights. Any additional mass that is added to the vehicle should be securely and rigidly attached.

1.5 Suspension Settling

This activity should be performed twice; firstly to check that the normal ride attitude, as defined in section 1.6 below, is within the manufacturer tolerances and secondly to measure the ride attitude just prior to performing the test, i.e. when all dummies are in the car and the car is ready to roll back from the block for the test. Please note that target and pin to record horizontal and vertical impact accuracy (section 9.3.3) should be fixed and aligned when second set of measurements is taken.

1.5.1 Roll the vehicle forwards by a distance of at least 1 metre

1.5.2 Roll the vehicle backwards by a distance of at least 1 metre

1.5.3 Repeat steps 1.5.1 and 1.5.2 for three complete cycles.

1.5.4 Measure and record the ride heights of the vehicle at the point on the wheel arch in the same transverse plane as the wheel centres. Do this for all four wheels.

1.6 Normal Ride Attitude

1.6.1 After following the above procedures the vehicle is in its Normal Ride Attitude when the vehicle attitude is in running order positioned on the ground, with the tyres inflated to the recommended pressures, the front wheels in the straight-ahead position, with maximum capacity of all fluids necessary for operation of the vehicle, with all standard equipment as provided by the vehicle manufacturer, with a 75 kg mass placed on the driver's seat and with a 50 kg mass placed on the front passenger's seat, and with the suspension set for a driving speed of 56 km/h in normal running conditions specified by the manufacturer (especially for vehicles with an active suspension or a device for automatic levelling). The manufacturer shall specify the Normal Ride Attitude with reference to the vertical (Z) position of any marks, holes, surfaces and identification signs on the vehicle body, above the ground. These marks shall be selected such as to be able to easily check the vehicle front and rear ride heights and vehicle attitude.

1.6.2

Note: Tolerances to manufacturers design position ad procedure to follow if these are not met still need to be determined if the AE-FW test is intended to be used to take compatibility measures with a high resolution load cell wall.

1.6.3 All ride heights measured are the Normal Ride Attitude ride heights.

2 INTRUSION MEASUREMENTS

2.1 Before test

2.1.1 Determine and mark the centre of the clutch, brake and accelerator pedals.

2.1.2 Set the steering wheel to its mid-position, if it is adjustable for either rake or reach (for full description of how to do this, see section 6)

2.1.3 Remove the centre of the steering wheel or, if fitted, the airbag assembly to expose the end of the steering column. When doing this, carefully note the connections to the airbag which will need to be remade on re-assembly. Follow the manufacturer's instructions when removing the airbag and/or steering wheel assemblies.

2.1.4 Determine and mark the centre of the top of the steering-column.

2.1.5 Remove the carpet, trim and spare wheel from the luggage compartment. The plastic trim or rubber seals that might influence the latching mechanism should be re-fitted once the intrusion measurements have been recorded. This is to ensure that any opening of the rear door during the impact is not caused by the omission of some part of the trim around the latching mechanism.

2.1.6 Locate the vehicle axis reference frame (see Figure 2.1) centrally to the rear of the vehicle.

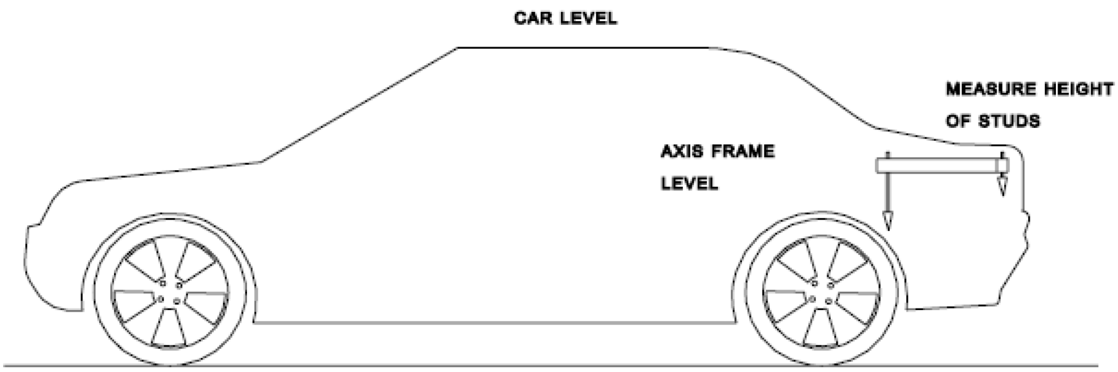


Figure 2.1: Setting up axis reference frame

2.1.7 Level the reference frame

2.1.8 Measure and record the stud heights of the reference frame. These will be used after the test to help reset the reference frame, if required.

2.1.9 If it is necessary to lean on the vehicle to reach the following points, the vehicle should be supported to maintain the ride heights during measuring.

2.1.10 Set up the vehicle co-ordinate axes in the 3D arm or similar device.

2.1.11 Mark and record the position of at least 5 datum points on the rear of the vehicle. These points should be on structures which are not expected to be deformed in the

test and should be positioned such that they have wide spaced locations in three dimensions and can all be reached with the 3D measuring system in one position.

2.1.12 Working on the passenger side of the vehicle determine and mark the positions of the B-post which are

i) at a distance of 100mm above the sill
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

2.1.13 All points should be as close as possible to the rubber sealing strip around the door aperture.

2.1.14 Measure and record the pre-impact positions of the two aperture points.

2.1.15 Working on the driver's side of the vehicle determine and mark the positions on the A and B-post which are

i) at a distance of 100mm above the sill
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

2.1.16 All points should be as close as possible to the rubber sealing strip around the door aperture.

2.1.17 Use the arm to measure the pre-impact positions of the centre of the top of the steering-column and the four door aperture points.

2.1.18 Record the position of the centre of the undepressed clutch, brake and accelerator pedals and where applicable foot operated parking brake. If the pedal is adjustable, set it to the mid position or a reasonable variation from this in accordance with the manufacturer's recommendations for the 50th percentile position.

2.1.19 Replace the steering wheel and airbag assembly. Check that all bolts are securely fastened. Ensure that all connections to the airbag are replaced and check the dashboard light to confirm the circuit is functional.

2.1.20 For optional additional intrusion measurements for compatibility please see section 2.3. Please note that these should be recorded for all FIMCAR project tests.

2.2 After test

2.2.1 Before dummy removal measure the distance between all foot pedals and a fixed point in the footwell e.g. seat runner, seat mounting bolt. If access cannot be gained remove the dummies according to section 9.6, taking care not to disturb any pedals and then record the measurement. This measurement should be re-checked before the pedals are measured with the 3D measuring system. If the pedal has moved re-position the pedal using the measurement taken previously.

2.2.2 Remove the dummies according to section 9.6 and remove the data acquisition and emergency abort equipment (if fitted) from the luggage compartment.

2.2.3 Remove the centre of the steering wheel or airbag assembly.

2.2.4 Use any 3 of the 5 datum points at the rear of the vehicle, and their pre-impact measurements, to redefine the measurement axes.

2.2.5 If the axes cannot be redefined from any 3 of the datum points relocate the axis reference frame in the same position as in section 2.1.8. Set the studs of the frame to the same heights as in section 2.2.11 (figure 2.2). The frame should now be in the same position relative to the car as it was before impact. Set up measurement axes from the frame.

2.2.6 Record the post-impact positions of the B-post points on the passenger's side of the vehicle.

2.2.7 Compare the vertical co-ordinate of the B-post sill point before (section 2.1.12) and after (section 2.2.5) the test.

2.2.8 Find the angle θ that best satisfies the following equation: $z = -x'\sin\theta + z'\cos\theta$ for the B-post sill point (where z = pre impact vertical measurement and x',z'= post-impact longitudinal and vertical).

2.2.9 Working on the driver's side of the vehicle, record the post-impact co-ordinates of the centre of the steering column, the centre of the clutch, brake and accelerator pedals, and where applicable a foot operated parking brake, with no load applied to them and in the blocked position (loaded with 200N to produce the maximum moment about the pedal pivot), the door aperture points. Prior to the 'blocked' pedal measurement, i.e. with the 200N applied, the brake fluid shall be removed to avoid the build up of hydraulic pressure. If the steering column has become detached during impact due to the operation of the shear capsules, the column should be repositioned before measurement in the upward and lateral directions so that it is in contact with whatever structure(s) last constrained it from further movement. If any of the foot pedals become detached do not take a measurement of that pedal.

2.2.10 Transform the post impact longitudinal and vertical measurement (x',z') using the following equations.

$$\begin{pmatrix} X' \\ Z' \end{pmatrix} = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} x' \\ z' \end{pmatrix}$$

2.2.11 Where ϑ is the angle determined in Section 2.2.8. X and Z should now be in the same frame of reference as the pre-impact measurements. [1]

2.2.12 From the pre-impact and adjusted post-impact data collected, determine

i. the longitudinal, lateral and vertical movement of the centre of the top of the steering column
ii. the longitudinal and vertical movement of all of the foot operated pedals
iii. the rearward movement of the A-post at waist level
iv. the reduction in width of the door aperture at waist and sill levels.

2.2.13 Record these intrusion measurements in the test details.

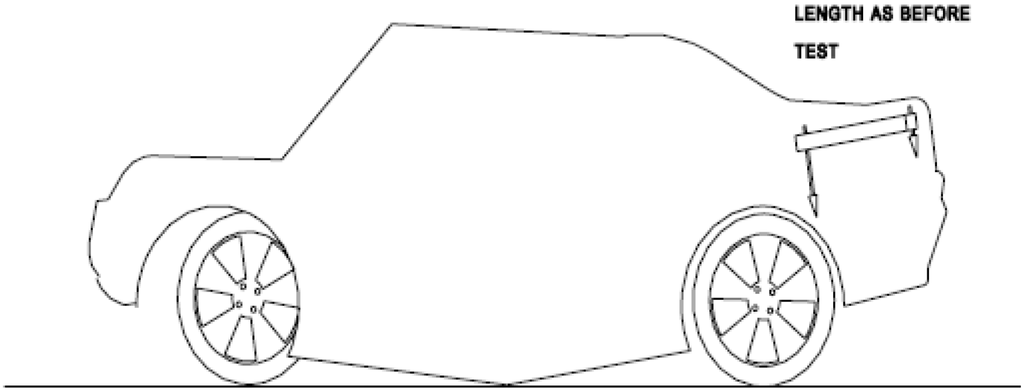


Figure 2.2: Re-setting axis reference frame after test

[1] This assumes that the point on the passenger B-post sill is not displaced vertically or laterally during the impact.

2.3 [Optional intrusion measurements]

Note: These measurements should be taken for all tests performed in the FIMCAR project.

Vehicle Pre-Test Measurements	
	Required
Door Apertures at waist and sill level	X
All Accelerometer Positions	X
Steering Wheel Centre	X
Pedal Centres	X
Pedal axis (outboard end of clutch pedal)	X
Dashboard / Footwell Points	Compatibility footwell grid and dash points (see below for details)

Compatibility Intrusion Measurements (pre- and post-test)

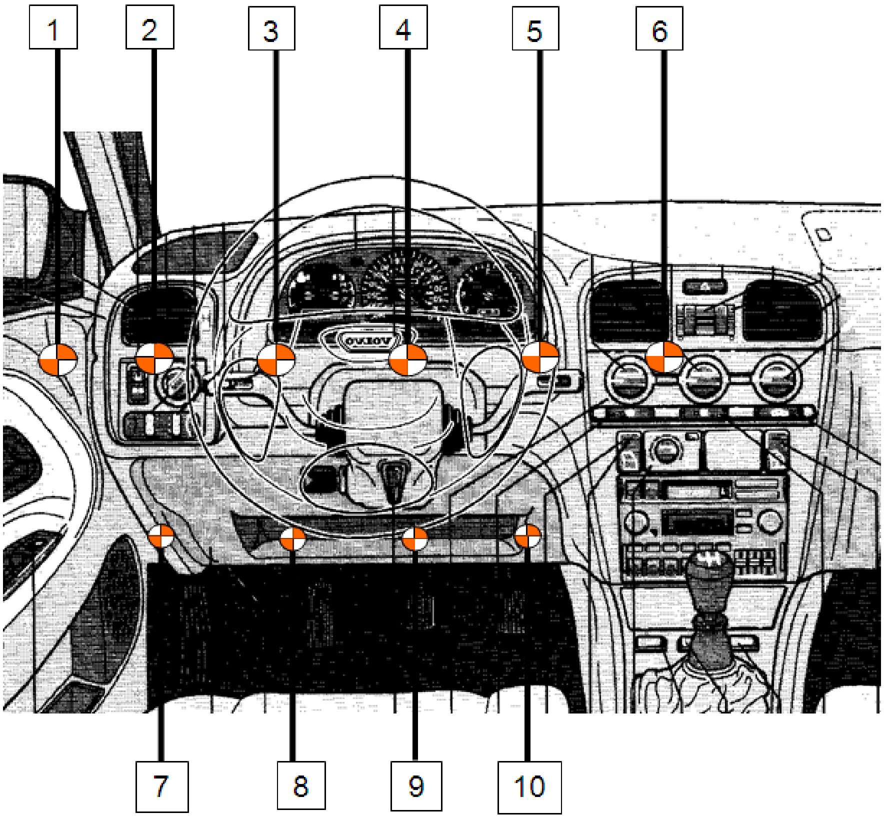
2.3.1 Instrument Panel Top (IPT)

1. Locate front lower corner of the side window in Z.
2. Locate outer edge of IP within height Z to Z+25mm and place target sticker 1.
3. Locate subsequent target stickers every 100mm (at the height defined by 2) inboard until the centreline of the vehicle. (typically 6 stickers)

Note: Z is positive in the downwards direction

2.3.2 Instrument Panel Base (IPB)

1. Locate the highest point along the centreline of the seat squab and determine height in Z and distance from vehicle centreline
2. Locate target sticker in on nearest point on the IP in the same Z height and distance from the vehicle centreline.
3. Locate target stickers every 100mm inboard and outboard along the IP until the centre console and the outer edge of the IP is reached



2.3.3 Problems with IP target location

If significant deviation is needed then best judgement is needed and the criteria that need consideration are:

1. Try to locate target stickers on major components of the instrument panel.

   Example
   Do not locate on the steering column surround as this will move independently of the majority of the IP.

2. At all times try to maintain the target stickers in the Z and X axis defined and only vary the Y axis by 100mm.

   Example

   If going below the instrument binnacle requires less deviation than proceeding around the top then place the target stickers in the former position.

2.3.4 Footwell Intrusion

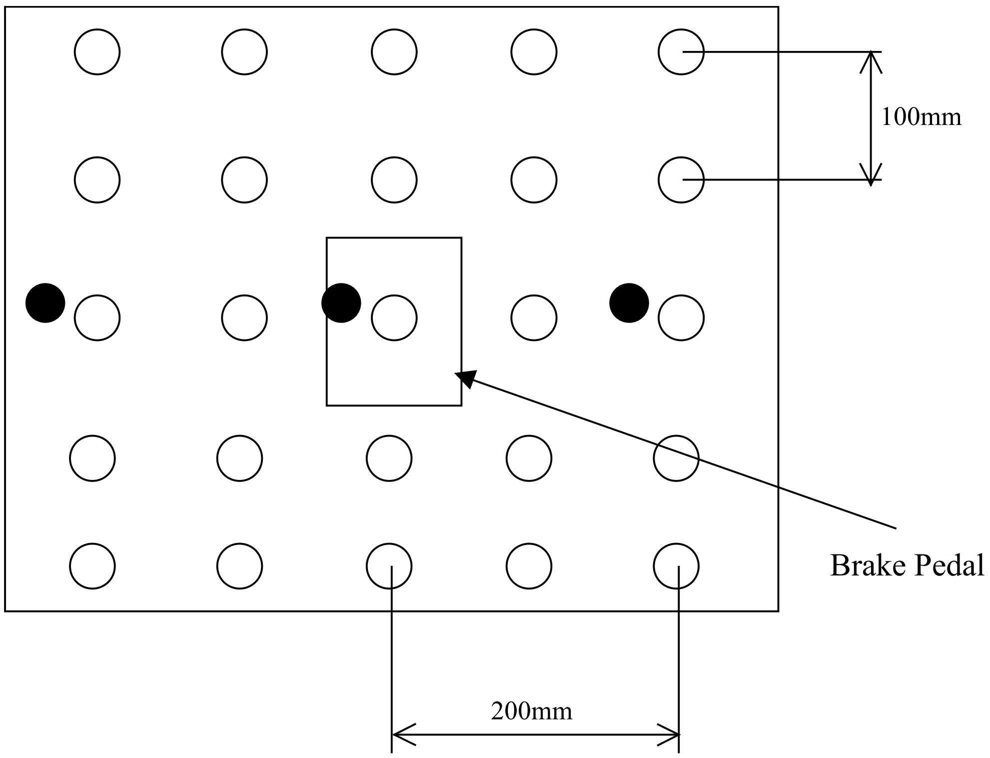
Minimum footwell intrusion measurements are the three black marked points behind the brake pedal.

If more measurements will be performed please follow the recommendations:

1. Remove all carpet from the footwell requiring measurement.
2. Locate a target sticker behind the brake pedal in the same X and Z location as that brake pedal.
3. Place a pre-cut carpet with holes spaced at 100mm in the footwell and locate one of the pre-cut holes over the target sticker defined in 2. (Carpet can follow the contours

of the footwell). If pre-cut carpet not available, use the 3D Arm to position target stickers.

4. Locate additional target stickers in the location of the pre-cut holes. Only place stickers up to a maximum of 200 mm either side of the brake pedal. Place stickers up to a maximum of 200 mm (if possible) above and 300mm below the point defined in 2.
5. If locations tie up with local features on the footwell (such as drain holes) then move target sticker the minimum distance to clear such feature.



3 DUMMY PREPARATION AND CERTIFICATION

3.1 General

3.1.1 Hybrid III test dummies should be used for the front seat driver and passenger positions. They should conform to U.S. Department of transportation, Code of Federal Regulations Part 572 Subpart E and ECE Regulation No. 94, except for modifications and additions stated later – See Section 3.3.

3.2 Dummy Certification

Full details of the certification procedure for the Hybrid-III dummy are available elsewhere (see Part 572 Subpart E of US Department of Transportation Code of Federal Regulations and Annex 10 of ECE Regulation No. 94). No manufacturer shall have access to any pre-test information regarding the test equipment to be used in the test, or be permitted to influence it selection in any way.

3.2.1 The Hybrid-III dummies should be re-certified after every THREE impact tests. With exception to the knee slider, which shall be certified to 10mm after every NINE impact tests.

3.2.2 If an injury criterion reaches or exceeds its normally accepted limit (e.g. HIC of 1000) then that part of the dummy shall be re-certified.

3.2.3 If any part of the dummy is broken in a test then the part shall be replaced with a fully certified component.

3.2.4 Copies of the dummy certification certificates will be provided as part of the full report for a test.

3.3 Additions and Modifications to the Hybrid III Dummies

3.3.1 The additions and modifications which will change the dynamic behaviour of the test dummies from Part 572E specification dummies are:

3.3.2 Ford 45 degree dorsi-flexion ankles/feet with rubber bump stops and padded heels are fitted.

3.3.3 Roller ball-bearing knees, such as those supplied by ASTC, shall be fitted.

3.3.4 Extra instrumentation is also fitted such as enhanced instrumented lower legs and a 6-axis neck. See Section 4 for a full instrumentation list.

3.3.5 Foam neck shields, such as those supplied by ASTC, must be fitted to the driver and passenger if a frontal protection airbag is present.

3.3.6 Dummy Clothing and Footwear

3.3.7 Hybrid-III dummies

3.3.8 Each dummy will be clothed with formfitting cotton stretch garments with short sleeves and pants which should not cover the dummy's knees.

3.3.9 Each dummy shall be fitted with shoes equivalent to those specified in MIL-S13192 rev P. (size XW)

3.4 Dummy Test Condition

3.4.1 Dummy Temperature

3.4.1.1 The dummy shall have a stabilised temperature in the range of 19^{o}C to 22^{o}C.

3.4.1.2 A stabilised temperature shall be obtained by soaking the dummy in temperatures that are within the range specified above for at least 5 hours prior to the test.

3.4.1.3 Measure the temperature of the dummy using a recording electronic thermometer placed inside the dummy's flesh. The temperature should be recorded at intervals of exceeding 10 minutes.

3.4.1.4 A printout of the temperature readings is to be supplied as part of the standard output of the test.

3.4.2 Dummy Joints

All constant friction joints should have their 'stiffness' set by the following method

3.4.2.1 Stabilise the dummy temperature by soaking in the required temperature range for at least 5 hours.

3.4.2.2 The tensioning screw or bolt which acts on the constant friction surfaces should be adjusted until the joint can just hold the adjoining limb in the horizontal. When a small downward force is applied and then removed, the limb should continue to fall.

3.4.2.3 The dummy joint stiffnesses should be set as close as possible to the time of the test and, in any case, not more than 24 hours before the test.

3.4.2.4 Maintain the dummy temperature within the range 19° to 22°C between the time of setting the limbs and up to a maximum of 10 minutes before the time of the test.

3.4.3 Dummy face painting

3.4.3.1 With the exception of the Hybrid-III face, the dummies should have masking tape placed on the areas to be painted using the size table below. The tape should be completely covered with the following coloured paints. The paint should be applied close to the time of the test to ensure that the paint will still be wet on impact.

Hybrid-IIIs

Eyebrows (left and right) Red

Nose Green

Chin Yellow

Left Knee Red

Right Knee Green

Left Tibia (top to bottom) Blue, Green, Red, Yellow

Right Tibia (top to bottom) Yellow, Red, Green, Blue

NOTE: The tape should be completely covered with the coloured paints specified.

Paint Area Sizes:

Hybrid-IIIs

Eyebrows = (25/2) x 50mm

Nose = 25 x 40mm strip, down nose centre line

Chin = 25 x 25mm square, centre line of chin

Knees = 50 x 50mm square, knee centre line with bottom edge level with top

of tibia flesh

Tibias = 25mm x 50mm, 4 adjacent areas down leg centre line with top edge

level with top of tibia flesh

front, extending to the head C of G at each side.

3.5 Post Test Dummy Inspection

3.5.1 The dummies should be visually inspected immediately after the test. Any lacerations of the skin or breakages of a dummy should be noted in the test specification. A dummy may have to be re-certified in this case. Refer to Section 3.2.

4 INSTRUMENTATION

All instrumentation shall be calibrated before the test programme. The Channel Amplitude Class (CAC) for each transducer shall be chosen to cover the Minimum Amplitude listed in the table. In order to retain sensitivity, CACs which are orders of magnitude greater than the Minimum Amplitude should not be used. A transducer shall be re-calibrated if it reaches its CAC during any test. All instrumentation shall be re-calibrated after one year, regardless of the number of tests for which it has been used. A list of instrumentation along with calibration dates should be supplied as part of the standard results of the test. The transducers are mounted according to procedures laid out in SAE J211 (1995). The sign convention used for configuring the transducers is stated in SAE J211.

4.1 Dummy Instrumentation

Hybrid-III

Location	Parameter		Minimum Amplitude	Driver No of channels	Passenger No of channels
Head	Accelerations, A_x A_y A_z		250g	3	3
Neck	Forces	F_x F_y	9kN	2	2
		F_z	14kN	1	1
	Moments, M_x M_y M_z		290Nm	3	3
Chest	Accelerations, A_x A_y A_z		150g	3	3
	Deflection, D_{chest}		100mm	1	1
Pelvis	Accelerations, A_x A_y A_z		150g	3	3
Femurs (L & R)	Forces, F_z		20kN	2	2
Knees (L & R)	Displacements, D_{knee}		19mm	2	2
Upper Tibia (L & R)	Forces, F_x F_z		12kN	4	4
	Moments, M_x M_y		400Nm	4	4
Lower Tibia[2] (L & R)	Forces, F_x F_z (F_y)		12kN	4	4
	Moments, M_x M_y		400Nm	4	4
	Total Channels per Dummy			36	36
	Total Channels			72	

[2] Note that for both dummies the measurement of F_y is at the laboratory's discretion.

4.2 Vehicle Instrumentation

4.2.1 The vehicle is to be fitted with an accelerometer on each B-post. The accelerometers are to be fitted in the fore/aft direction (Ax)

4.2.2 Remove carpet and the necessary interior trim to gain access to the sill directly below the B-post.

4.2.3 Securely attach a mounting plate for the accelerometer horizontally on to the sill, without adversely affecting seat belt retractors and/or pretensioners.

4.2.4 Fix the accelerometer to the mounting plate. Ensure the accelerometer is horizontal to a tolerance of ±1 degree and parallel to the X-axis of the vehicle.

4.2.5 Attach lightweight (<100g) seatbelt loadcells to the shoulder section of the driver and passenger seatbelts. For FIMCAR tests also attach lightweight (<100g) seatbelt loadcells to the lap section of the driver and passenger seatbelts.

VEHICLE

Location	Parameter	Minimum Amplitude	No of channels
B-Post LHS	Accelerations, A_x	150g	1
B-Post RHS	Accelerations, A_x	150g	1
Driver Seatbelt Shoulder Section	Force, $F_{diagonal}$	16kN	1
Passenger Seatbelt Shoulder Section	Force, $F_{diagonal}$	16kN	1
	Total Channels per Vehicle		4

Accelerometers for compatibility measures, note these should be included for all FIMCAR project tests

4.2.6 Additional accelerometers

Vehicle Instrumentation (Accelerometers)						
Location	X	CAC	Y	CAC	Z	CAC
RHS A-Pillar Lower	**X**	**750**				
LHS A-Pillar Lower	**X**	**750**				
RHS A-Pillar above Dash	**X**	**750**				
LHS A-Pillar above Dash	**X**	**750**				
Engine Top, Central	**X**	**2000**				
Engine Sump, Central	**X**	**2000**				
Gearbox, Central	**X**	**2000**				
RHS B-Pillar Lower	**X**	**250**				
LHS B-Pillar Lower	**X**	**250**				
Rear Cross Beam, Central	**X**	**250**	**X**	**250**	**X**	**250**
Tunnel at C of G	**X**	**250**	**X**	**250**	**X**	**250**
Tunnel at Rate Sensor	**X**	**250**	**X**	**250**	**X**	**250**
Subframe (when Present)	**X**	**2000**				
Total Channels	**19**					

Note:

To summarise and to get an overview over all used sensors, please use the following table for the documentation:

Number	Location	ISO code	Long name
001	RHS A-Pillar Lower	?3APILRILO00AC??	A-Pillar Right Lower
002	LHS A-Pillar Lower	?1APILLELO00AC??	A-Pillar Left Lower
003	RHS A-Pillar above Dash	?3APILRIMI00AC??	A-Pillar Right Middle
004	LHS A-Pillar above Dash	?1APILLEMI00AC??	A-Pillar Left Middle
005	Engine Top, Central	?0ENGNTP0000AC??	Engine Top
006	Engine Sump, Central	?0ENGNBO0000AC??	Engine Bottom
007	Gearbox, Central	?0GEAR000000AC??	Gear Box
008	RHS B-Pillar Lower	?6BPILRILO00AC??	B-Pillar Right Lower
009	LHS B-Pillar Lower	?4BPILLELO00AC??	B-Pillar Left Lower
010	Rear Cross Beam, Central	?8CRMEREMI00AC??	Cross Member Rear Middle
011	Tunnel at C of G	?5TUNNCD0000AC??	Tunnel CoG
012	Tunnel at Rate Sensor	?0CEUN000000AC??	Central Unit
013	Subframe (when Present)	??SUFR????00AC??	Sub Frame
014	Additional vehicle channel(s)		
...	Dummy channels		
....	LCW channels		

4.2.7 Event switches

1	Time Zero Event T01
2	Time Zero Event T02
3	VEHICLE AIRBAG SENSOR TRIGGER TIME USING 2 CURRENT CLAMPS

Note: for FIMCAR project tests Time Zero Event contact should be included between barrier and car and vehicle and current clamps should be used to sense airbag trigger time for all airbags.

4.2.8 Rate Sensor

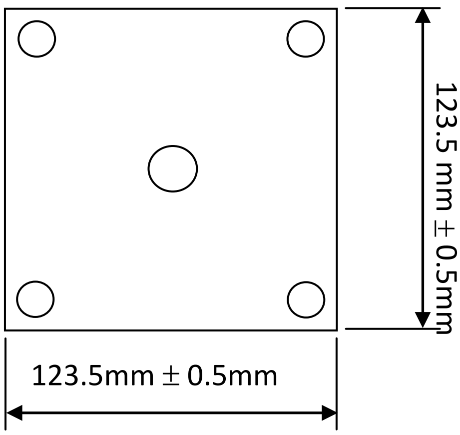
Rate sensor positioned at tunnel C. of G.

4.3 [Load Cell Wall]

4.3.1 The load cell wall is to be formed by a matrix of individual load cells with a spacing of 125 mm in the horizontal and vertical directions. The centre spacing of the load cells is 125 mm x 125 mm. The width of the load cell wall is to be equal to or greater than the width of the deformable barrier and to be exactly divisible by 250 mm. The height is to be equal to or greater than the height of the deformable element. [Width 2000 mm, height 1000 mm]. The lower edge of the load cell wall is to be parallel to the ground and at a height of 80 mm relative to the ground. The load cell wall is to be rigidly attached to the barrier with its front face in the same plane as the front face of the barrier.

Dimensions and layout

4.3.2 Each load cell tile on the load cell wall (LCW) has a nominal frontal area of 125 mm x 125 mm. However, when mounted on the LCW the load cells must have sufficient clearance between the adjacent cells to prevent interaction of the load cell tiles under maximum shear loads. The suggested external dimensions of each individual load cell face in the LCW are shown.



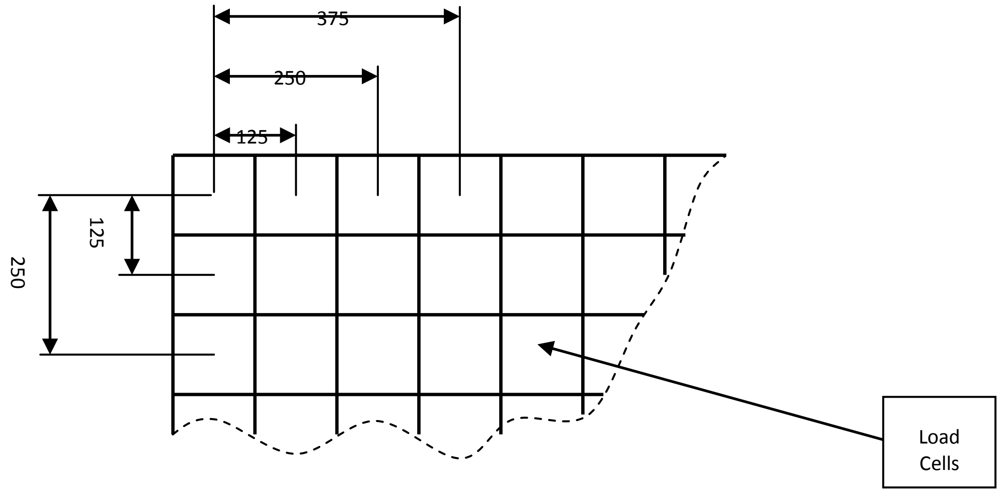
4.3.3 Each load cell shall be faced with an 18 mm thick MDF panel the same size as the load cell face. Any of these MDF facings which become damaged (e.g. dented, split, etc.) should be replaced with undamaged MDF facings.

4.3.4 Each load cell must have threaded holes on the loading face to allow the mounting of deformable barrier faces and the MDF facings. A suggested pattern of holes is shown in the previous figure.

4.3.5 The full load cell wall, for the purposes of the FWDB test, is to comprise of 128 load cells arranged in a matrix of cells 16 wide by 8 high. The full LCW should have frontal dimensions of 2000 mm wide by 1000 mm high. The height of the bottom of the LCW above ground should be adjustable. [For the FWDB test, the height of the bottom of the LCW above ground is 80 mm.]

4.3.6 The load cells shall be spaced such that the centre of each load cell is 125 mm apart in the vertical and horizontal direction. This spacing shall be measured from the centre of the uppermost corner cell on the load cell wall in order to avoid

compound errors. This can be achieved by mounting the load cells on a backplate to provide the precise location of each load cell.



4.3.7 The impact face of the load cell wall, including MDF facings, should be flat - no cell should be either recessed or protrude relative to any of its surrounding cells. The surface flatness is check by offering up a flat edge to the load cell wall – this flat edge should bridge two or more load cells. There should be no visible gap [greater than 0.5mm] between the flat edge and the surface of a load cell. If any cells are found to protrude or be recessed, remedial action should be taken to correct this.

Technical Specifications

Nominal area of each load cell impact face	125 x 125mm
Rated load	300kN
Safe overload	600kN
Shear load	100kN
Offset loading error	< 3% (300kN)
Linearity error	< 1.1% (300kN)
Compression / Shear load crosstalk	< 0.5% (300kN)
Cell Mass	< 6kg
Mass difference tolerance between load cells	± 0.2kg
Dynamic response	> 10kHz
Resonant frequency	> 5kHz
Operational temperature range	$0^{o}C$ to $+70^{o}C$

Note :- Processing of LCW data should be carried out with a filter of CFC60

5 CAMERA LOCATIONS

All cameras 1000 fps

Note: For indication of camera angles see Euro NCAP test protocol.

Camera No.	Camera Type	Shot Content
1	1000 fps high speed	Driver (tight)
2	1000 fps high speed	Driver (wide)
3	1000 fps high speed	Passenger (tight)
4	1000 fps high speed	Passenger (wide)
5	1000 fps high speed	Plan view (wide – whole car)
6	1000 fps high speed	Plan view (tight)
7	1000 fps high speed	Front view driver & passenger
8	1000 fps high speed	Driver (wide – whole car)
9	1000 fps high speed	Underside (pit) view engine bay including subframe attachment to firewall

6 PASSENGER COMPARTMENT ADJUSTMENTS

Vehicle adjustments

Adjustment	Required Setting	Notes	Methods
Seat Fore/Aft	Mid position as defined in Section 6.1	May be set to first notch rearwards of mid position if not lockable at mid position	See Section 6.1
Seat Base Tilt	Manufacturer's design position	Permissible up to Mid Position	See Section 6.1.11
Seat Height	Lowest position		
Seat Back Angle (as defined by torso angle)	Manufacturer's design position	Otherwise 25° to vertical As defined by Torso angle	See Section 7.1.1
Front Head Restraints	Highest position		
Head Restraint Tilt	Manufacturer's design Position	Otherwise mid position	
Seat Lumbar Support	Manufacturer's design position	Otherwise fully retracted	See Section 6.1.12
Steering wheel - vertical	Mid position		See Section 6.3
Steering wheel - horizontal	Mid position		See Section 6.2
Rear Head Restraints	Remove or Lowest	Unless instructed otherwise by the manufacturer	
Rear Seat Fore/Aft	Mid position		See Section 6.4.1
Rear Seat Facing	Forwards		See Section 6.4.1
Arm-rests (Front seats)	Lowered position	May be left up if dummy positioning does not allow lowering	
Arm-rests (Rear seats)	Stowed position		
Glazing	Front - Lowered Rear - Lowered or Removed	This applies to opening windows only	
Gear change lever	In the neutral position		
Pedals	Normal position of rest		
Doors	Closed, not locked		
Roof	Lowered	Where applicable	
Sun Visors	Stowed position		
Rear view mirror	Normal position of use		
Seat belt anchorage	Manufacturer's 50th percentile design position	If no design position then set to mid-position, or nearest notch upwards	

Note:- Adjustments not listed will be set to mid-positions or nearest positions rearward, lower or outboard.

6.1 Determination of and Setting the Fore/aft, Tilt and Lumbar Settings of the Seats

6.1.1 The manufacturers seat fore/aft position which corresponds to the 95th percentile male seating position will have been provided.

6.1.2 Place a mark on the moving part of seat runner close to the unmoving seat guide.

6.1.3 Move the seat to its most forward position of travel.

6.1.4 Mark the unmoving seat guide in line with the mark on the seat runner. This corresponds to the seat in its most forward position.

6.1.5 Move the seat to the position of its travel provided for the 95th percentile male.

6.1.6 Mark the unmoving seat guide in line with the mark on the seat runner. This corresponds to the 95th percentile male's seating position.

6.1.7 Measure the distance between the forwards and rearwards marks. Place a third mark on the seat guide mid-way between the forwards and rearwards marks

6.1.8 Move the seat so that the mark on the seat runner aligns with the mark on the seat guide.

6.1.9 Lock the seat at this position. Ensure that the seat is fully latched in its runners on both sides of the seat. The seat is now defined as being at its 'mid seating position'. The vehicle will be tested with the seat in this position.

6.1.10 If the seat will not lock in this position, move the seat to the first locking position that is rear of the mid seating position. The vehicle will be tested with the seat in this position.

6.1.11 If the seat base is adjustable for tilt it may be set to any angle from the flattest up to its mid position according to the manufacturer's preference. The same seat tilt setting must be used for frontal and side impact.

6.1.12 If the seat back is adjustable for lumbar support it should be set to the fully retracted position, unless the manufacturer specifies otherwise or the dummy prevents this.

6.2 Setting the Steering Wheel Horizontal Adjustment

6.2.1 Choose a part of the facia that is adjacent to the steering column and can be used as a reference.

6.2.2 Move the steering wheel to the most forward position of its travel

6.2.3 Mark the steering column in line with an unmoving part of the facia. This corresponds to the most forward travel of the steering wheel.

6.2.4 Move the steering wheel to the most rearwards position of its travel Mark the steering column in line with an unmoving part of the facia. This corresponds to the most rearwards travel of the steering wheel.

6.2.5 Measure the distance between the forwards and rearwards marks on the steering column. Place a third mark on the steering column mid-way between the forwards and rearwards marks. This corresponds to the centre of travel of the steering wheel.

6.2.6 Move the steering wheel so that the mark on the steering column aligns with the facia.

6.2.7 Lock the steering column at this position. The steering wheel is now in its mid position of travel. The vehicle will be tested with the steering wheel in this position.

6.3 Setting the Steering Wheel Vertical Adjustment

A method that is in principle the same as Section 6.2 should be used to determine and set the steering wheel vertical adjustment to the mid position. It is unlikely that the same part of the facia used during the setting procedures for the horizontal adjustments could be used for the vertical adjustment. Care should be taken to avoid unintentional adjustment of the horizontal setting during the vertical adjustment procedure.

7 DUMMY POSITIONING AND MEASUREMENTS

The table detailing the timetable for dummy position and measurements found under the section heading is replaced with the following table:-

Timetable	*When this is done*
1. Determine the H-point of the driver's seat	Day before test
2. Determine the H-point of the passenger seat	Day before test
3. Dummy installation	Test day
4. Dummy placement	
5. Dummy positioning	
6. Dummy positioning	

7.1 Determine the H-Point of front seats

The device to be used is the H-point machine as described in SAE J826. If the seat is new and has never been sat upon, a person of mass 75 ± 10kg should sit on the seat for 1 minute twice to flex the cushions. The seat shall have been at room temperature and not been loaded for at least 1 hour previous to any installation of the machine.

<u>For Driver's Seat</u>

7.1.1 Set the seat back so that the torso of the dummy is as close as possible to the manufacturers reasonable recommendations for normal use. In absence of such

recommendations, an angle of 25 degrees towards the rear from vertical will be used.

7.1.2 Place a piece of muslin cloth on the seat. Tuck the edge of the cloth into the seat pan/back join, but allow plenty of slack.

7.1.3 Place the seat and back assembly of the H-point machine on the seat at the centre line of the seat.

7.1.4 Set the thigh and lower leg segment lengths to 401 and 414mm respectively.

7.1.5 Attach lower legs to machine, ensuring that the transverse member of the T-bar is parallel to the ground.

7.1.6 Place right foot on undepressed accelerator pedal, with the heel as far forwards as allowable. The distance from the centre line of the machine should be noted.

7.1.7 Place left foot at equal distance from centre line of machine as the right leg is from centre line. Place foot flat on footwell.

7.1.8 Apply lower leg and thigh weights.

7.1.9 Tilt the back pan forwards to the end stop and draw the machine away from the seatback.

7.1.10 Apply a 10kg load twice to the back and pan assembly positioned at the intersection of the hip angle intersection to a point just above the thigh bar housing.

7.1.11 Return the machine back to the seat back.

7.1.12 Install the right and left buttock weights.

7.1.13 Apply the torso weights alternately left and right.

7.1.14 Tilt the machine back forwards to the end stop and rock the pan by 5 degrees either side of the vertical. The feet are NOT to be restrained during the rocking. After rocking the T-bar should be parallel to the ground.

7.1.15 Reposition the feet by lifting the leg and then lowering the leg so that the heel contacts the floor and the sole lies on the undepressed accelerator pedal.

7.1.16 Return the machine back to the seat back.

7.1.17 Check the lateral spirit level and if necessary apply a lateral force to the top of the machine back, sufficient to level the seat pan of the machine.

7.1.18 Adjust the seat back angle to the angle determined in 7.1.1, measured using the spirit level and torso angle gauge of the H-point machine. Ensure that the torso remains in contact with the seat back at all times. Ensure that the machine pan remains level at all times.

7.1.19 Measure and record in the test details the position of the H-point relative to some

7.1.20 easily identifiable part of the vehicle structure

For Passenger's Seat

Follow the procedure for the determination of the driver's H-point ensuring that the distance from the centre line to the legs is the same as that used in the determination of the driver's H-point. For both right and left feet, place the feet flat on the floor.

7.2 Dummy Installation

It is the intention that the dummy should not be left to sit directly on the seat for more than 2 hours prior to the test. It is acceptable for the dummy to be left in the vehicle for a longer period, provided that the dummy is not left in overnight or for a similarly lengthy period. If it is known that the dummy will be in the vehicle for a time longer than 2 hours, then the dummy should be sat on plywood boards placed over the seat. This should eliminate unrealistic compression of the seat.

7.3 Dummy Placement

Driver dummy (50th percentile Hybrid III)

7.3.1 Ensure that the seat is in the correct position as defined by Section 6.1.

7.3.2 Place the dummy in the seat with the torso against the seat back, the upper arms against the seat back and the lower arms and hands against the outside of the upper leg.

7.3.3 Carefully place the seat belt across the dummy and lock as normal.

7.3.3.1 Apply a small rearwards force to the lower torso and a small forwards force to the upper torso to flex the upper torso forwards from the seat back. Then rock the torso left and right four times, going to between 14 and 16 degrees to the vertical.

7.3.3.2 Maintaining the small rearwards force to the lower torso, apply a small rearwards force to the upper torso to return the upper torso to the seat back. Slowly remove this force.

Passenger dummy (5th percentile Hybrid III)

Follow procedure in FMVSS208 Section 16.3.3.

7.4 Front Driver Dummy Positioning

Dummy positioning should be carried out immediately before the test and the vehicle should not be moved or shaken thereafter until the test has begun. If a test run is aborted and the vehicle brought to a standstill using an emergency braking method, the dummy placement procedure should be repeated. If the dummy, after three attempts cannot be positioned within the tolerances below then it is to be placed as close to the tolerance limits as possible.

Record this in the test details.

7.4.1 H-point

The dummy's H-point shall be within 13mm in the vertical dimension and 13mm in the horizontal dimension of a point 6mm below the H-point as determined in Section. Record the position of the dummy H-point in the test details.

7.4.2 Pelvic Angle

The pelvic angle measurement gauge should read 22.5° ± 2.5° from the horizontal. Record the measured angle in the test details.

7.4.3 Head

The transverse instrumentation platform of the head shall be horizontal to within 2.5°

Levelling of the head shall be carried out in this order:

-Adjust the H-point within the limit (par. 7.5.1)

-Adjust the pelvic angle within the limits (par. 7.5.2)

-Adjust the neck bracket the minimum to ensure that the transverse instrumentation platform is level within limits. Record the measured angle in the test details.

7.4.4 **Arms**

The driver's upper arms shall be adjacent to the torso as far as is possible. The passenger's arms shall be adjacent to the torso and in contact with the seat back.

7.4.5 Hands

The driver dummy's hands shall have their palms placed against the steering wheel at a position of a quarter to three. The thumbs should be lightly taped to the wheel.

The passenger's hands should be placed with the palms in contact with the outside of the legs and the little finger in contact with the seat cushion.

7.4.6 Torso

The dummies' backs should be in contact with the seat back and the centre line of the dummies should be lined up with the centre line of their respective seats.

7.4.7 Legs

The upper legs of both dummies shall be in contact with the seat cushion as far as possible. The distance apart of the outside metal surfaces of the knees of each dummy shall be 270mm ± 10mm (except if the left foot is placed on a footrest in par. 7.5.8 below). The legs of the dummies should be in vertical longitudinal planes as far as is possible.

7.4.8 Feet

The driver dummy's right foot shall rest on the undepressed accelerator pedal with the heel on the floor. If the foot cannot be placed on the pedal then it should be placed as far forwards as possible with the foot perpendicular to the lower tibia, in line with the centre line of the pedal. The left foot should be placed as flat as possible on the toe-board parallel to the centre line of the vehicle. If any part of the left foot is in contact with a foot-rest or wheel arch when in this position then place the foot fully on this rest providing a normal seating position can still be achieved. Keep the legs in the same vertical longitudinal plane. The knee gap requirement of 270mm ± 10mm may be ignored in this case. Note the knee gap in the test details.

The passenger dummy's feet shall be placed with the heel as far forwards as possible and the feet as flat as possible. Both feet shall be parallel to the centre line of the vehicle.

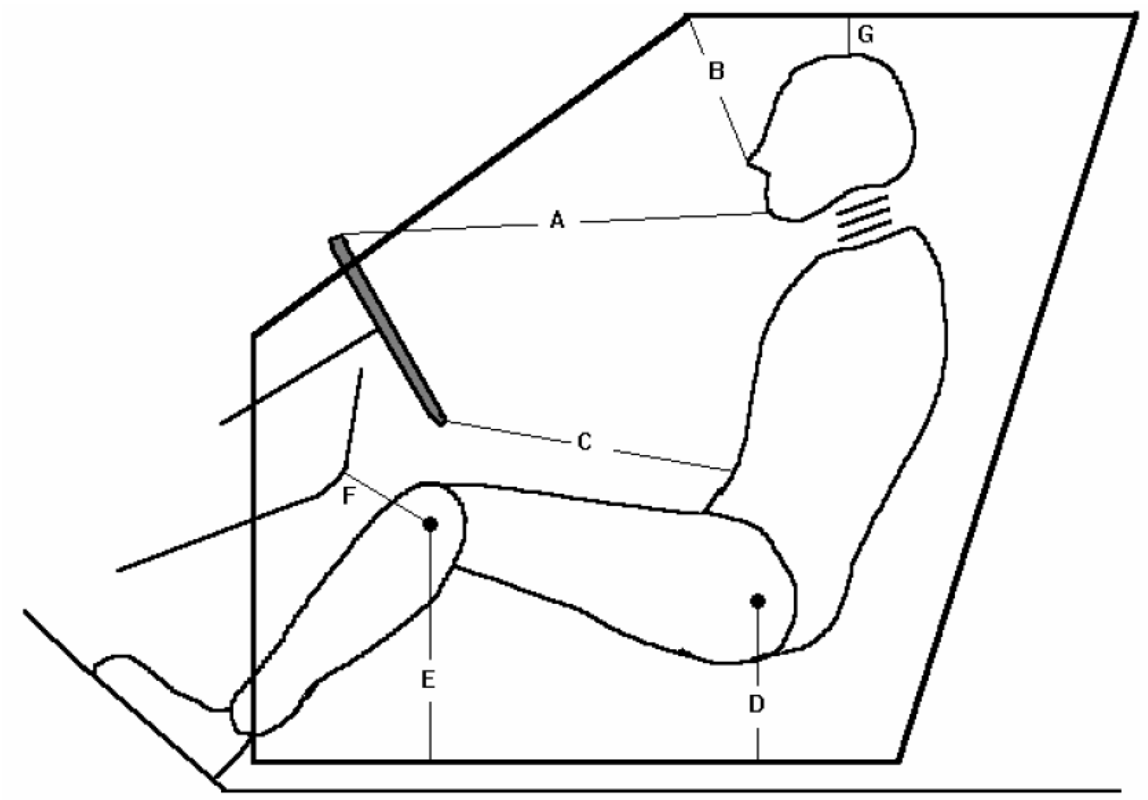
7.5 Front Passenger Dummy Positioning

Follow procedure in FMVSS208 Section 16.3.3.

7.6 Dummy Measurements

The following measurements are to be recorded prior to the test after the dummy settling and positioning procedures have been carried out.

Front Seated Dummies



Recording dummy position – Pre-test

Driver's Side		Passenger's Side	
A	Chin to top of rim	A	Chin to facia
B	Nose to top edge of glass	B	Nose to top edge of glass
C	Stomach to rim	C	Stomach to facia*
D	H-point to top of sill	D	H-point to top of sill
E	Knee bolt to top edge of sill	E	Knee bolt to top edge of sill
F	Knee bolt to top edge of bolster	F	Knee bolt to top edge of bolster*
G	Head to roof surface	G	Head to roof surface
θ	Neck Angle	θ	Neck Angle
	H-Point Co-ordinates (to vehicle)		H-Point Co-ordinates (to vehicle)
α	Seat back angle (as defined by torso angle)	α	Seat back angle (as defined by torso angle)

* Shortest distance

8 STILL PHOTOGRAPHY

The following photographs will be taken pre and post-test unless otherwise indicated. Pre-test photographs will be taken with the dummies in their final positions.

1 Front view of barrier.

2 Side view of barrier.

3 Side view of barrier at 45 degrees to front.

4 Side view of barrier with vehicle.

5 Car RHS, with camera centred on junction of B-post waist, showing full car.

6 Car RHS, with camera centred on B-post waist, showing rear passenger compartment.

7 Car RHS, with camera aimed at waist height, showing driver's compartment.

8 Car RHS at 45 degrees to front.

9 Front view of car.

10 Car LHS at 45 degrees to front.

11 Car LHS, with camera aimed at waist height, showing front passenger's compartment.

12 Car LHS, with camera centred on B-post waist, showing rear passenger compartment.

13 Car LHS, with camera centred on B-post waist, showing full car.

14 Driver and seat to show driver compartment and position of seat relative to the sill.

15 To show area immediately in front of driver.

16 To show driver's footwell area and location of dummy's feet and pedals.

17 Passenger and seat to show compartment and position of seat relative to sill.

18 To show area immediately in front of passenger.

19 To show passenger footwell area and dummy's feet.

20 *Overall view of where the car has come to rest after impact (including barrier).]

21 *To show position of all door latches and/or open doors.

22 *To show driver knee contacts with facia (airbag should be lifted if obscuring view).

23 *To show passenger knee contacts with facia (airbag should be lifted if obscuring view).

After Dummy Removal

24 Passenger compartment from rear window.

25 LHS interior from RHS of car.

26 RHS interior from LHS of car.

27 LHS front door area.

28 RHS front door area.

29 Facia.

30 Passenger footwell.

31 Driver footwell.

32 Steering wheel taken perpendicular to driver's side.

33 Driver right knee impact point.

34 Driver left knee impact point.

35 Passenger knee impact area.

36 Positions of all accelerometers

37 Position of rate sensor

Note: The above photos are for a RHD car, for a LHD car camera locations will switch sides.

9 TEST PARAMETERS

9.1 Load Cell Wall and Deformable Barrier

9.1.1 A high resolution Load Cell Wall as described in section 4.3 is included in the protocol as an option. Please note that for all APROSYS project tests the LCW should be included in all tests.

9.1.2 A deformable barrier as described in section 11 is included in the protocol as an option. Please note that for APROSYS project tests the deformable barrier should be included in appropriate tests.

9.2 Speed

9.2.1 Measure the speed of the vehicle as near as possible to the point of impact.

9.2.2 This speed should be 56km/h +/-1km/h. Record the test speed in the test details.

TARGET SPEED = 50km/h ± 1km/h

9.3 Alignment of vehicle to barrier

The fore/aft centre line of the vehicle is to be aligned with the vertical centre line of the deformable element facing the barrier.

9.3.1 Alignment of the load cell wall

The lower edge of the load cell wall is to be parallel to the ground and at a height of 80 mm relative to the ground. The load cell wall is to be rigidly attached to the barrier with its front face in the same plane as the front face of the barrier. The load cell wall must not overlap the edges of the barrier.

9.3.2 Alignment of deformable element

The lower edge of the deformable element, excluding the mounting flanges, is to be aligned with the lower edge of the load cell wall. The vertical centreline of the deformable element is to be aligned with the vertical centre line of the load cell wall. In order to attach the deformable element to the load cell wall, the MDF facings on the lower row of load cells are to extend below the lower edge of the load cells. The barrier is fixed to the load cell wall by means of a clamping plate along the upper edge and along the lower edge.]

9.3.3 Record the horizontal and vertical accuracy

TARGET OVERLAP = 100%

9.4 Door Opening Forces

9.4.1 Check that none of the doors have locked during the test

9.4.2 Try to open each of the doors (front doors followed by rear doors) using a spring-pull attached to the external handle. The opening force should be applied perpendicular to the door, in a horizontal plane, unless this is not possible. The manufacturer may specify a reasonable variation in the angle of the applied force. Gradually increase the force on the spring-pull, up to a maximum of 500N, until the door unlatches. If the door does not open record this then try to unlatch the door using the internal handle. Again attempt to open the door using the spring-pull attached to the external handle. Record the forces required to unlatch the door and to open it to 45° in the test details.

9.4.3 If a door does not open with a force of 500N then try the adjacent door on the same side of the vehicle. If this door then opens normally, retry the first door.

9.4.4 If the door still does not open, record in the test details whether the door could be opened using extreme hand force or if tools were needed.

Note: In the event that sliding doors are fitted, the force required to open the door sufficiently enough for an adult to escape should be recorded in place of the 45^{o} opening force.

9.5 Dummy Removal

9.5.1 Do not move the driver or passenger seats. Try to remove the dummies.

9.5.2 If the dummies cannot be removed with the seats in their original positions, recline the seat back and try again. Note any entrapment of the dummy.

9.5.3 If the dummies can still not be removed, try to slide the seats back on their runners.

9.5.4 If the dummies can still not be moved, the seats can be cut out of the car.

9.5.5 Record the method used to remove the dummies.

9.6 Intrusion Measurements

Take the vehicle intrusion measurements. See Section 2.2 for a full description of how to do this.

10 CALCULATION OF INJURY PARAMETERS

This section of the Euro NCAP frontal impact testing protocol is replaced by the following. The following table lists all of the channels which are to be measured and the Channel Frequency Class at which they are to be filtered. Traces should be plotted of all of these channels. The injury calculation column lists the parameters which will be calculated for each location. If the injury parameter is not a simple peak value and involves some further calculation, details are given subsequently. Peak levels of head or neck parameters occurring from impacts after the dummy head rebounds from an initial contact are not considered when calculating maximum levels of injury parameters.

Location	**Parameter**	**CFC**[3]	**Injury Calculation**
Head	Accelerations, A_x A_y A_z	1000	Peak Resultant acceleration HIC_{36} HIC_{15} Resultant 3msec exceedence
Neck	Forces, F_x F_y F_z	1000	Tension (+F_z) continuous exceedence Shear (F_x) continuous exceedence Peak Extension (M_y)I Nij for US FMVSS208 SNPRM
	Moments, M_x M_y M_z	600	
Chest	Accelerations, A_x A_y A_z	180	Peak resultant acceleration Resultant 3 msec exceedence Peak deflection Viscous Criterion
	Deflection, D	180	
Pelvis	Accelerations, A_x A_y A_z	180	Peak resultant acceleration Resultant 3 msec exceedence
Femurs	Forces, F_z	600	Compressive Axial Force (-F_z)

(L & R)			Continuous exceedence
Knees (L & R)	Displacements, D	180	Peak displacement
Upper Tibia (L & R)	Forces, F_x F_z	600	Peak displacement
	Moments, M_x M_y	600	Peak Tibia Compression ($-F_z$) Tibia Index
Lower Tibia (L & R)	Forces, F_x F_z	600	Peak Tibia Compression ($-F_z$) Tibia Index
	Moments, M_x M_y	600	

[3] All CFCs taken from SAE J211

Using the above channels, dummy injury parameters can be calculated according to the following procedures:

10.1 Head

10.1.1 Calculate the resultant head acceleration AR from the three components Ax, Ay and Az after they have been filtered and determine the maximum value of AR

$$A_R = \sqrt{A_X^2 + A_Y^2 + A_Z^2}$$

10.1.2 Determine the highest value of the resultant head acceleration

10.1.3 Calculate the Head Injury Criterion (HIC) according to

$$HIC = (t_2 - t_1)\left[\frac{\int_{t1}^{t2} A_R . dt}{(t_2 - t_1)}\right]^{2,5}$$

where AR is expressed in multiples of g. Maximise HIC for any time 'window' (t2 – t1) up to 36 milliseconds.

10.1.4 Determine the acceleration level which AR exceeds for a cumulative time period of three milliseconds i.e. the head 3msec exceedence.

10.2 Neck

10.2.1 Calculate the neck extension bending moment from

$$\left(M_y\right)i = M_y - fx.d$$

Where My and Fx are bending moment and shear force respectively measured at the transducer and d is the distance from the transducer to the interface

(d=0.01778). See (SAEJ1733).

10.2.2 Determine the 'continuous exceedence' of both the neck tension (Fz positive) and neck shear (Fx) forces.

$$C_{(t)} = \frac{D_{(t)}}{0{,}229}$$

10.3 Chest

V is the velocity of deflection and is calculated as the differential of the deflection with respect to time:

$$V_{(t)} = \frac{8 * \left[D_{(t+1)} - D_{(t-1)}\right] - \left[D_{(t+2)} - D_{(t-2)}\right]}{12\delta t}$$

where δt is the time interval between successive digital samples of D(t). Calculate V(t)*C(t) continuously with time and determine its greatest value.

10.4 Femurs

10.4.1 For each of the femurs, calculate the continuous exceedence in compression (Fz negative)

10.5 Knees

10.5.1 For each of the knees, determine the greatest value of the knee displacement D

10.6 Tibia

10.6.1 At the upper and lower of both the left and the right tibias, calculate the resultant bending moment MR from Mx and My after they have been filtered.

$$M_{R(t)} = \sqrt{M_{X(t)}^2 + M_{Y(t)}^2}$$

10.6.2 Calculate the Tibia Index (TI) at the upper and lower tibia of each leg according to the equation

$$TI_{(t)} = \left|\frac{M_{R(t)}}{(M_R)_C}\right| + \left|\frac{F_{Z(t)}}{(F_Z)_C}\right|$$

TI(t) is the instantaneous value of the Tibia Index at time t. (MR)C is the critical value of the bending moment = 225Nm and (FZ)C is the critical value of the axial force = 35.9kN. The vertical lines indicate that the modulus should be taken.

10.6.3 Determine the highest value of the Tibia Index.

10.6.4 Determine the highest value of the axial compressive force measured at either the upper or lower tibia.

11 DEFORMABLE BARRIER SPECIFICATION

The external dimensions of the barrier are illustrated in Figure C.1. The deformable element is formed from two layers of aluminium honeycomb, with an overall depth of 300 mm, a height of 1000 mm and a width of 2000 mm. [For larger vehicles the height and the width of the deformable element should be increased in 125 mm increments vertically and 250 mm *increments horizontally to ensure that no part of the vehicle directly impacts the LCW.]*

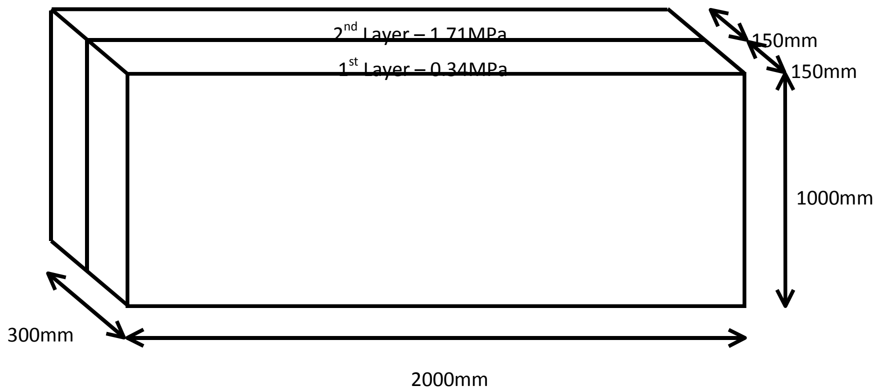


Figure C.1: Full Width Deformable Barrier external dimensions (not to scale).

The first (front) layer of the deformable element has a crush strength of 0.34 MPa and is 150 mm deep, the second (rear) layer has a crush strength of 1.71 MPa and is 150 mm deep. In addition, the second layer is segmented every 125 mm in the horizontal and vertical directions starting at 125 mm from the outer edges. The position of each of the slots is to be measured from the outer edge of the barrier to prevent compound errors. The two layers are joined with a muslin interlayer and there is to be no cladding on any faces other than the mounting face. The mounting face is the rear face of the 1.71 MPa layer. The mounting face is to be clad with a 0.5 mm aluminium sheet which protrudes a set distance of 40 mm from the upper and lower faces of the barrier to provide mounting flanges for attachment to the load cell wall.

Front honeycomb layer

Height: 1000 mm (in direction of honeycomb ribbon axis)

Width: 2000 mm

Depth: 150 mm (in direction of honeycomb cell axes)

Material: Aluminium 3003 (ISO 209, part 1)

Foil thickness: 0.076 mm

Cell size: 19.14 mm

Density: 28.6 kg/m3

Crush strength: 0.342 MPa +0% -10%

Rear honeycomb layer

Height: 1000 mm [□2.5 mm] (in direction of honeycomb ribbon axis)

Width: 2000 mm [□2.5 mm]

Depth: 150 mm [□1 mm] (in direction of honeycomb cell axes)

Material: Aluminium 3003 (ISO 209, part 1)

Foil thickness: 0.076 mm

Cell size: 6.4 mm

Density: 82.6 kg/ m3

Crush strength: 1.711 MPa +0% -10%

Backing sheet

Height: *1080 mm ± 2.5 mm*
Width: *2000 mm ± 2.5 mm*
Thickness: *0.5 mm ± 0.1 mm*
Material: *Aluminium 5251*

Deformable Barrier Face Construction

The rear honeycomb layer is segmented every 125 mm in the horizontal and vertical directions starting at 125 mm from the outer edges. The position of each of the segmentation slots is to be measured from the outer edge of the barrier to prevent compound errors. [The slot size is to be less than 5 mm wide.]

The rear honeycomb layer shall be bonded to the backing sheet with adhesive such that the cell axes are perpendicular to the sheet.

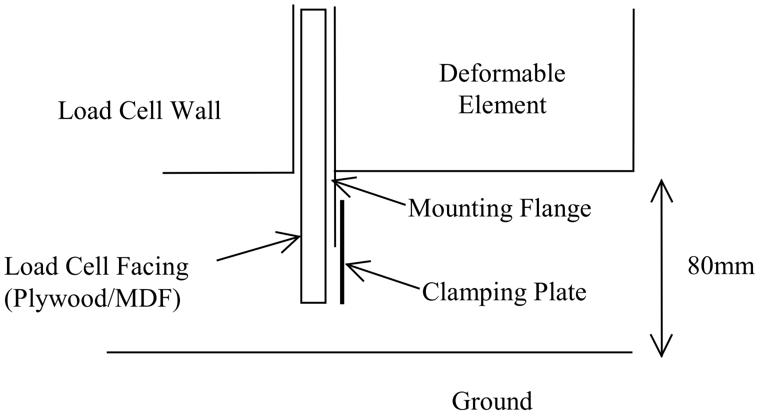
The front honeycomb layer shall be adhesively bonded to the rear honeycomb layer by means of a muslin interlayer sheet, such that the cell axes are perpendicular to the sheet. The deformable element is formed from two layers of aluminium honeycomb, with an overall depth of 300 mm, a minimum height and width of 1000 mm and 2000 mm respectively. [For larger vehicles the height and the width of the deformable element should be increased in 125mm increments vertically and 250 mm increments horizontally to ensure that no part of the vehicle directly impacts the LCW.]

The certification procedure that should be followed for the materials in the Full Width Deformable Barrier is described in Annex 9 Paragraph 2 of Regulation 94, these materials having a crush strength of 0.342 MPa and 1.711 MPa respectively.

The adhesive to be used throughout should be a two-part polyurethane (such as Ciba-Geigy XB5090/1 resin with XB5304 hardener, or equivalent). The adhesive bonding procedure that should be followed for materials in the Full Width Deformable Barrier is described in Annex 9 Paragraph 3 of Regulation 94.

Deformable Barrier Face Mounting

The lower edge of the deformable element, excluding the mounting flanges, is to be aligned with the lower edge of the load cell wall. The vertical centreline of the deformable element is to be aligned with the vertical centre line of the load cell wall. In order to attach the deformable element to the load cell wall, the MDF facings on the lower row of load cells are to extend below the lower edge of the load cells. The barrier is fixed to the load cell wall by means of a clamping plate along the upper edge and along the lower edge. The bolts used to attach the clamping plate must not pass through the mounting flange.



[If the impact area of the test vehicle were likely to exceed the upper edge of the deformable element when at the minimum height of 1000 mm, an alternative option to increasing the height of the deformable element would be to increase the height of the LCW relative to the ground. This is provided that the lower edge of the impact area is a minimum of 125 mm further from the ground level in the vertical direction than the lower edge of the deformable element when in the new position. The proposed increase in height would be in 125 mm steps beginning at 80 mm relative to the ground.]

12 COMPATIBILITY METRIC

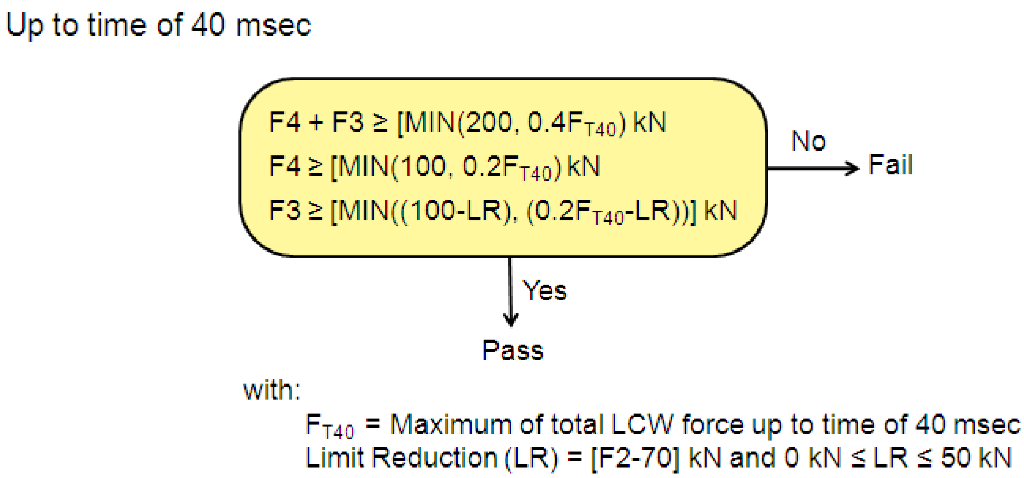


Figure C.2: FWDB Metric with Limit Reduction

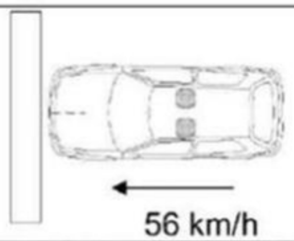
ANNEX D: FULL WIDTH TEST REPORTS

Table of Contents

SUPERMINI 1 FWDB 56 KM/H (1) @ BAST

FWDB Supermini 1

Test Date	05/02/2012
Location	BASt
Topic	Full Width test
Test Number	FM05C3FW
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1		Barrier:	Full Width 150 mm 0.34 MPa 150 mm 1.71 MPa Segmented
Brand/type	Supermini 1		
Impact side:	Front	Impact accuracy	8 mm left 0 mm
Speed:	56 km/h	LCW ground clearance	80 mm
Overlap:	100%	LCW / barrier dimensions	2000 mm wide 750 mm high
Test mass:	1301 kg		
Dummy:	LHS - Hybrid III 50th RHS - Hybrid III 5th		

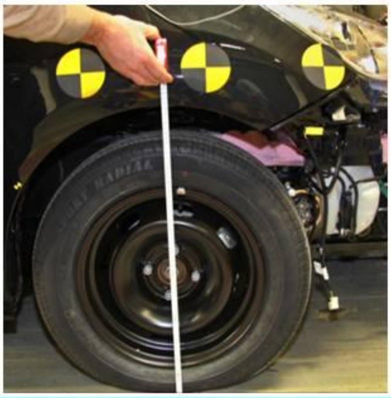
Test parameters

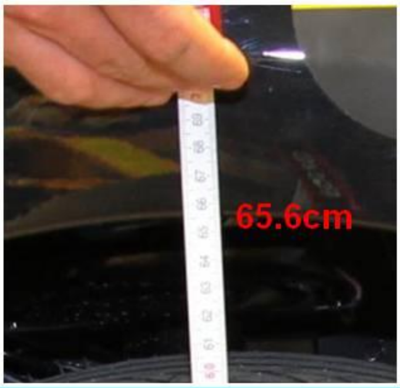
- **Vehicle data: Supermini 1, LHD**
- **Engine / Transmission: 1.4 l diesel / 5 gear**
- **Test speed: 56.02 km/h**
- **Test weight: F 757 kg / R 544kg Total 1301 kg**
- **Test impact accuracy: 8 mm left, 0 mm up**

- **Test vehicle status:**
  - **Not raised (references see next slides)**

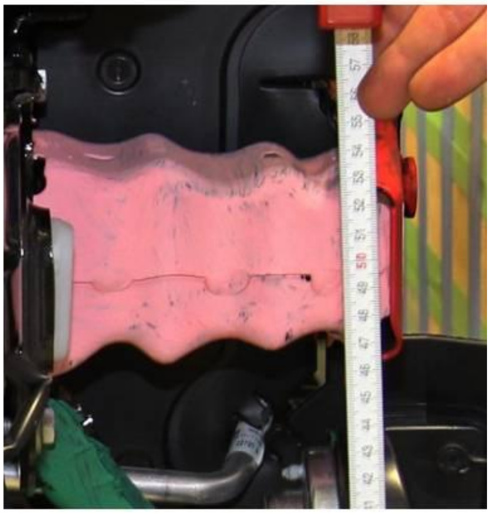
Car hight

Ride heights (wing edge to floor distance) [mm]		
	Left side	Right side
Front	650	654
Rear	635	643





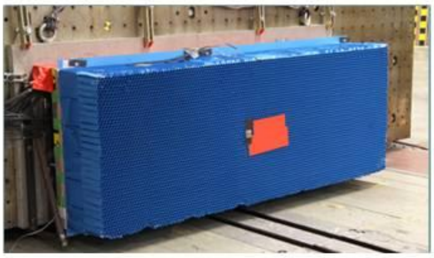
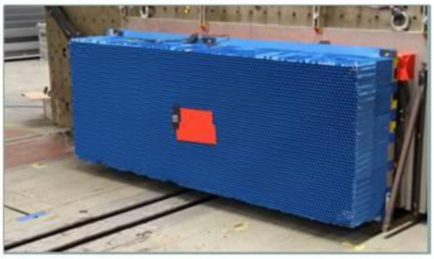
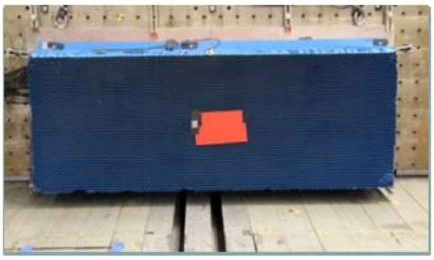
Car hight



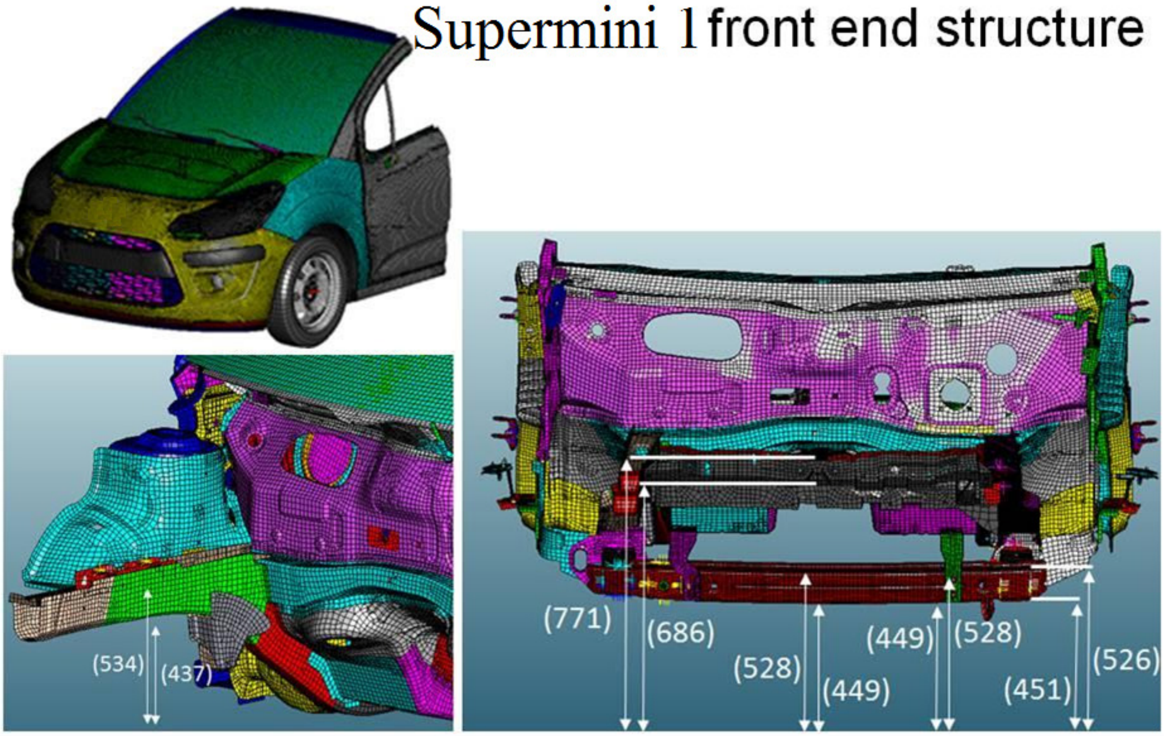
Pre-test Pictures



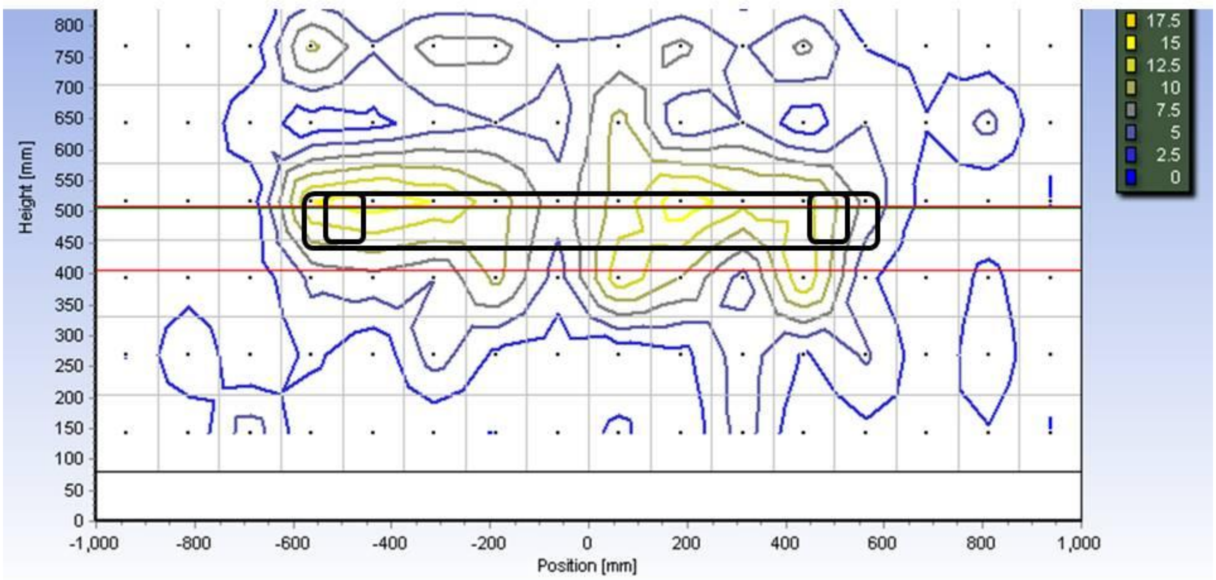

Pre-test Pictures
Barrier

Supermini 1 front end structure



Alignment of Vehicle Structure with LCW



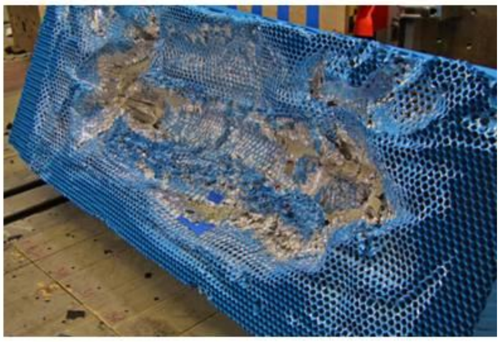
LCW Forces at 40 ms

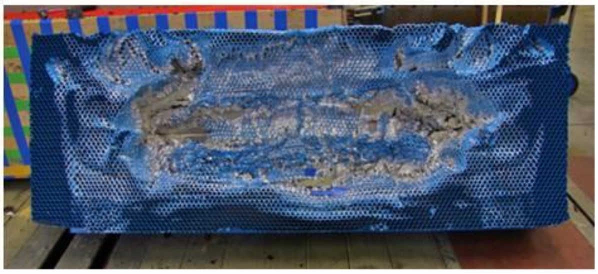
40.00 ms	-687.50	-562.50	-437.50	-312.50	-187.50	-62.50	62.50	187.50	312.50	437.50	562.50	687.50	812.50	937.50	Sum Rows
1017.50 [mm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
892.50 [mm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
767.50 [mm]	0.93	10.64	5.32	8.54	8.28	5.34	5.76	8.15	4.67	8.16	2.46	1.80	0.86	0.19	72.26
642.50 [mm]	4.23	0.94	1.77	3.82	4.92	3.86	10.94	3.08	4.98	0.88	4.99	2.62	5.80	0.02	53.10
517.50 [mm]	0.89	14.99	16.60	14.85	11.33	6.10	11.08	16.72	13.40	13.74	6.89	1.40	0.21	-0.01	131.04
392.50 [mm]	0.38	5.62	6.64	5.01	10.65	3.79	14.06	9.83	3.98	14.69	3.00	0.25	3.27	0.10	82.67
267.50 [mm]	0.05	3.19	0.22	6.30	1.90	0.91	0.27	1.57	6.40	2.14	5.37	0.77	4.23	0.31	38.48
142.50 [mm]	6.50	0.10	0.23	0.02	0.00	0.84	3.13	0.00	6.31	0.14	1.88	2.02	2.30	-0.08	24.31
Sum Columns	12.98	35.48	30.78	38.54	37.08	20.84	45.24	39.35	39.74	39.75	24.59	8.86	16.67	0.53	401.86

Post-test Pictures
Vehicle 1

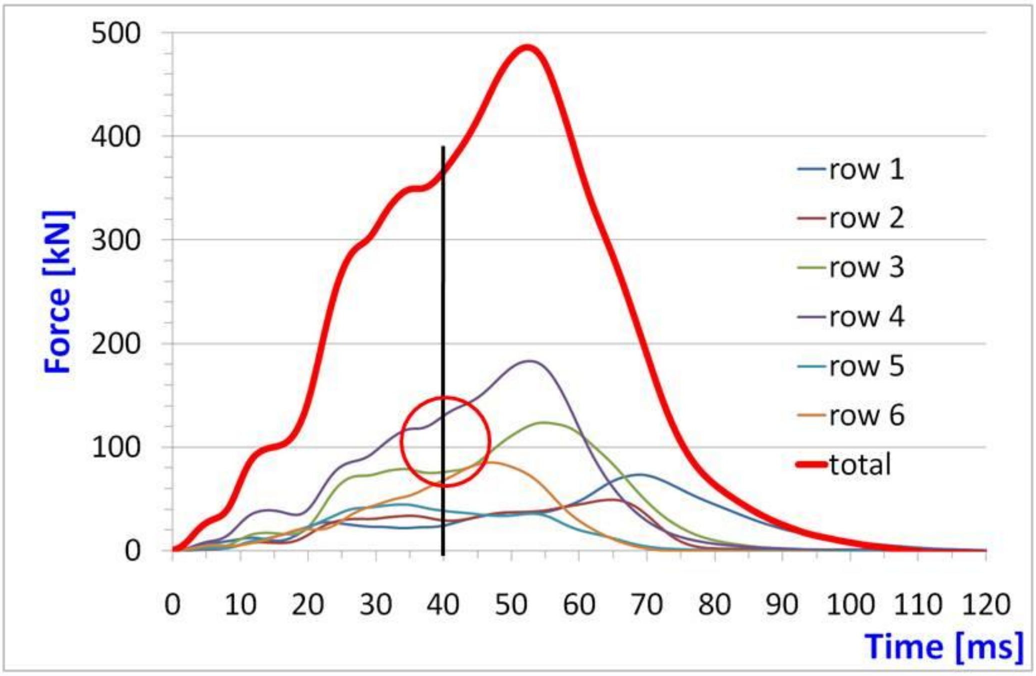
Post-test Pictures

Barrier

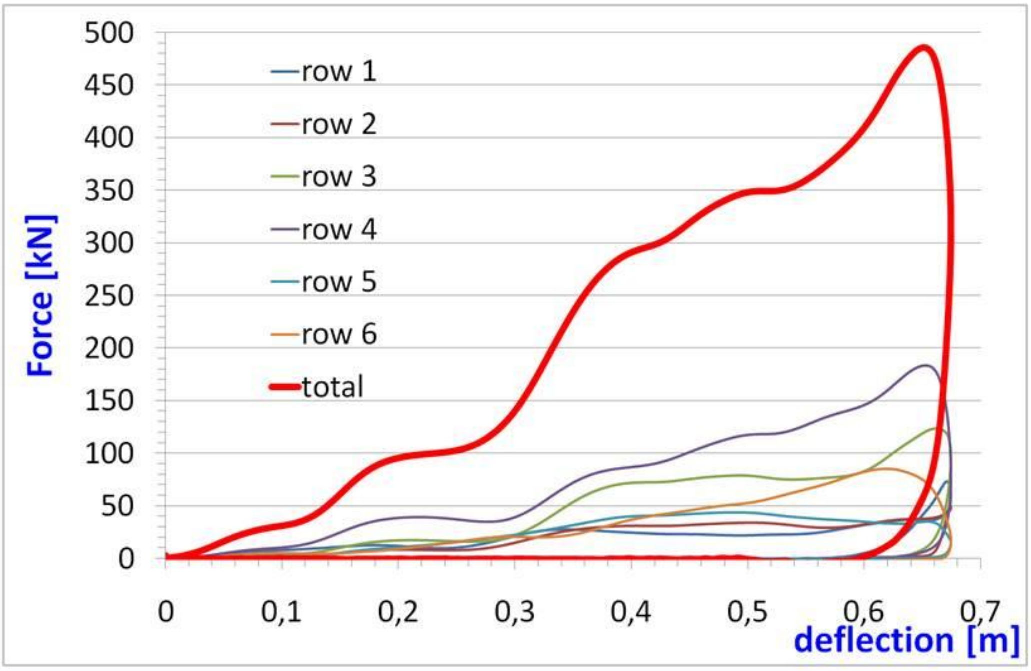




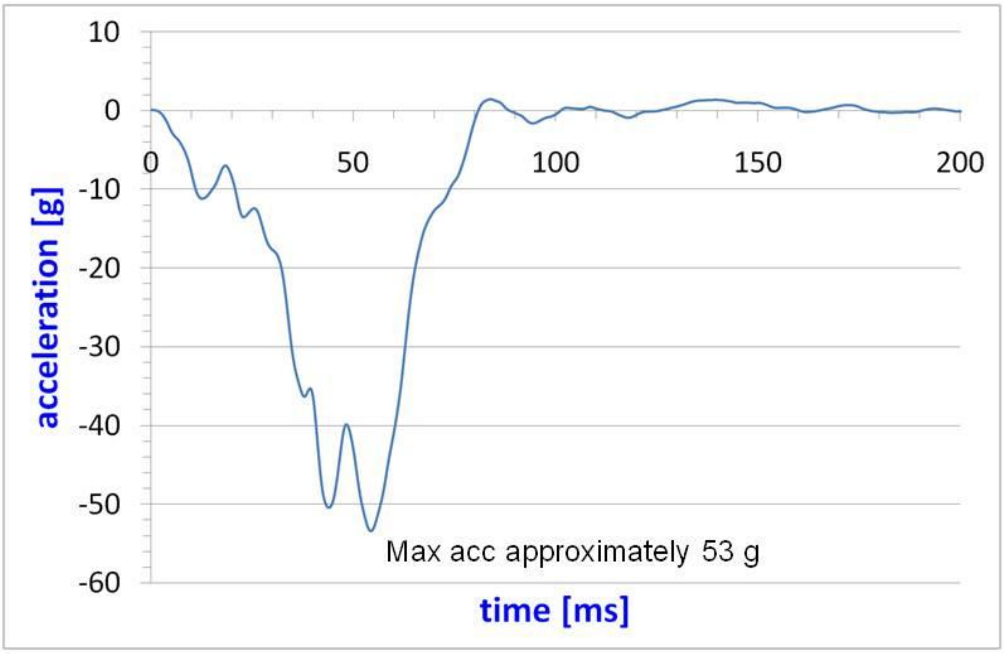
Plot: row forces over time



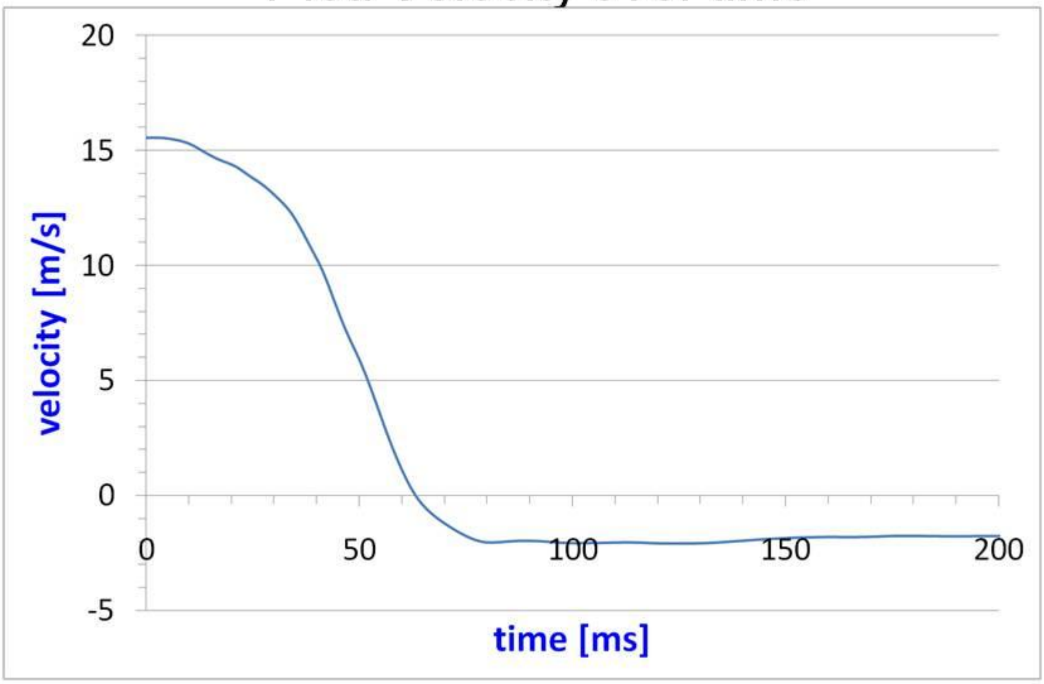
Plot: Row forces over deflection



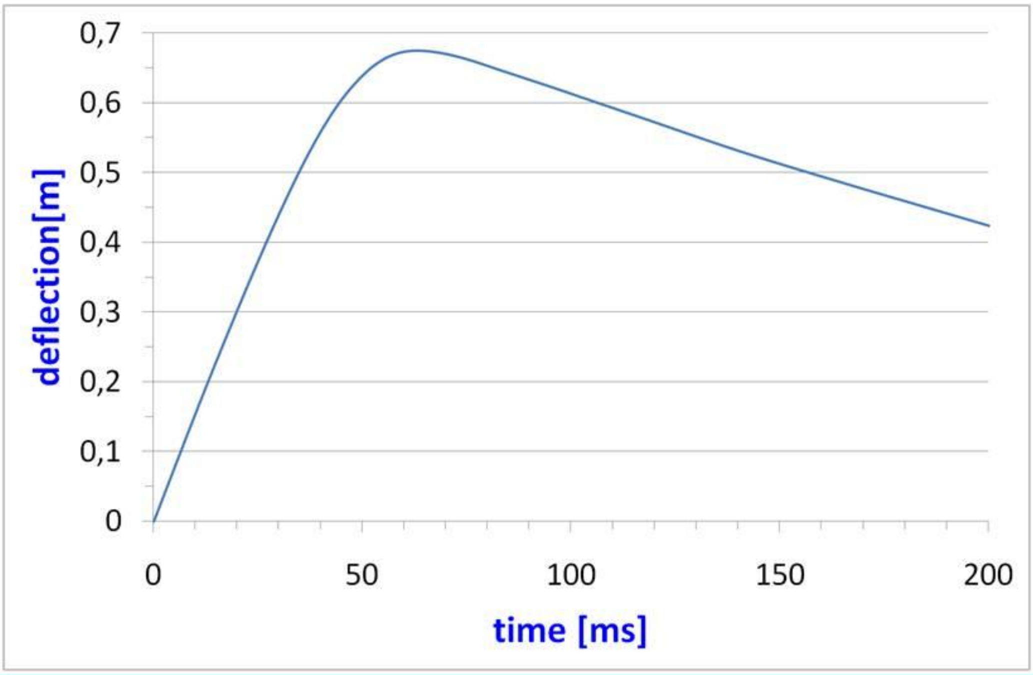
Plot: Vehicle acceleration (a+b pillar)



Plot: Velocity over time



Plot: Deflection over time



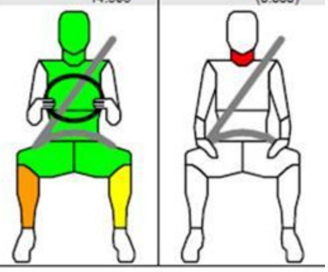
Dummy values FW Test

FM05C3FW	Type of Test	Supermini 1 vs. FWDB
FM05C3FW		Frontal Impact
2012-03-05	Regulation	Euro NCAP

Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (HF)		
Head & Neck			4.000 ★			0.000 ★
Head						
HIC 36	707.83			912.82		
Acceleration Resultant	72.31	g	4.000 ★	84.98	g	
3ms cumulative	71.23	g		84.43	g	
Neck						
Shear Force Fx+	0.65	kN	4.000 ★	0.10	kN	0.000 ★
Shear Force Fx-	-0.27	kN	4.000 ★	-0.35	kN	0.000 ★
Tensile Force Fz+	1.48	kN	4.000 ★	1.36	kN	0.000 ★
Extension My-	-10.63	Nm	4.000 ★	-35.09	Nm	
Chest			4.000 ★			
Deflection	-0.11	mm	4.000 ★	-27.55	mm	
VC max	0.25	m/s	4.000 ★	0.14	m/s	
belt at upper diagonal belt Force	5.32	kN		4.69	kN	
Femur & Knee			4.000 ★			
Left						
Femur Force Fz-	-0.29	kN	4.000 ★			
Knee Slider Displacement	-0.34	mm	4.000 ★			
Right						
Femur Force Fz-	-1.64	kN	4.000 ★			
Knee Slider Displacement	-0.45	mm	4.000 ★			
Tibia			2.596 ★			

FM05C3FW	Type of Test	Supermini 1 vs. FWDB
FM05C3FW		Frontal Impact
2012-03-05	Regulation	Euro NCAP

Left					
Compression Upper Fz-	-1.90	kN	4.000 ★	-0.75	kN
Compression Lower Fz-	-2.62	kN	3.585 ★	-1.04	kN
Tibia Index Upper	0.69		2.712 ★	0.86	
Tibia Index Lower	0.32		4.000 ★	0.62	
Right					
Compression Upper Fz-	-1.86	kN	4.000 ★	-0.66	kN
Compression Lower Fz-	-2.77	kN	3.488 ★	-0.84	kN
Tibia Index Upper	0.72		2.596 ★	0.59	
Tibia Index Lower	0.44		3.823 ★	0.32	
Sum			14.596		(0.000)



Rating without modifiers

Points
- ★ 4.000
- ★ 2.670 - 3.999
- ★ 1.330 - 2.669
- ★ 0.001 - 1.329
- ★ 0.000

Citroen C3	Load Cell Wall Fimcar	Results Passengers
56.02 km/h	0.0 km/h	Front
1300 kg	0 kg	Vehicle 1
Driver Left		

Dummy values Euro NCAP Test

Driver Passenger

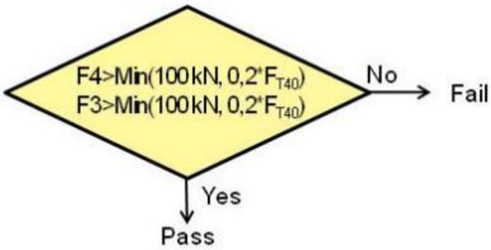
	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	44,93	4,000	42,97	4,000
HIC_{36}	350,03		333,44	
Resultant Acc. 3 msec exeedence - g	44,38		41,89	
Unstable airbag contact, Bottoming out or Hazardous deployment		0,000		0,000
Steering wheel displacement (-1) mm	-4	0,000		
Incorrect airbag deployment		0,000		0,000
Head Assessment		4,000		4,000
NECK				
Shear level exceeded - kN	0,42	4,000	0,37	4,000
duration of exceedence - ms	0		0,00	
Tension level exceeded - kN	1,40	4,000	1,26	4,000
duration of exceedence - ms	0		0,00	
Extension - Nm	18,40	4,000	27,80	4,000
Neck Assessment		4,000		4,000
Head and Neck Assessment		4,000		4,000
CHEST				
Compression - mm	31,16	2,691	29,24	2,966
Viscous criterion - m/s	0,13	4,000	0,11	4,000
Steering wheel contact (-1)		0,000		
A-Pillar displacement (-2) mm	-24	0,000		
Unstable passenger compartment (-1)		0,000		
Shoulder belt load - kN	5,33		4,98	
Chest Incorrect Airbag Deployment Modifier		0,000		0,000
Chest Assessment		2,691		2,966
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0,0	4,000	0,0	4,000
Left Femur Compression level exceeded - kN	0,21	4,000	0,1	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Left Knee, Femur and Pelvis Assessment		4,000		4,000
Right Knee Slide - mm	0,0	4,000	0,0	4,000
Right Femur Compression level exceeded - kN	0,16	4,000	0,2	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Right Knee, Femur and Pelvis Assessment		4,000		4,000

	Driver		Passenger	
Knee, Femur and Pelvis assessment		4,000		4,000
LOWER LEG				
Left compression - kN	2,14	3,907	1,55	4,000
Left Upper Tibia Index	0,47	3,689	0,38	4,000
Left Lower Tibia Index	0,26	4,000	0,23	4,000
Brake pedal vertical (-1) mm	-49	0,000		
Left Lower Leg assessment		3,689		4,000
Right compression - kN	0,92	4,000	1,42	4,000
Right Upper Tibia Index	0,42	3,911	0,39	4,000
Right Lower Tibia Index	0,29	4,000	0,22	4,000
Brake pedal vertical (-1) mm	-49	0,000		
Right Lower Leg assessment		3,911		4,000
FOOT and ANKLE				
Clutch pedal horizontal displacement - mm	-96	4,000		
Footwell Rupture (-1)		0,000		
Pedal Blocking (-1)	0	0,000		
Foot and Ankle assessment		4,000		
Lower Leg, Foot and Ankle assessment		3,689		4,000
SUMMARY				
Head and Neck assessment		4,000		4,000
Chest assessment		2,691		2,966
Knee, Femur and Pelvis assessment		4,000		4,000
Lower Leg, Foot and Ankle Assessment		3,689		4,000
TOTAL		14,380		14,966

TOTAL FRONTAL 14,380

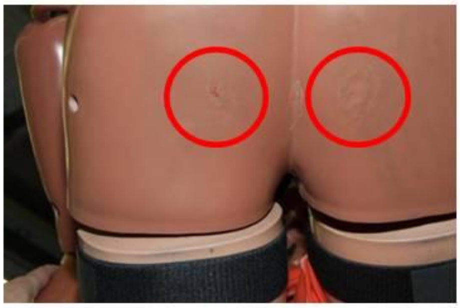
Metrics evaluation

	Supermini 1 FWDB, FM05C3FW		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	83	80,4	OK
F4 > MIN[100, 0.2Ft40]	131	80,4	OK
Global	OK		



Other findings

- Dummy pelvis were loaded due to seat pan structure



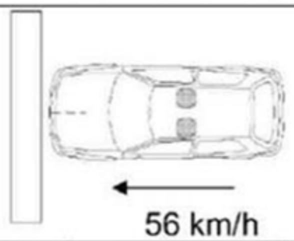
Conclusions

- Supermini 1 test with 56 km/h FWDB
- Max vehicle acceleration: 53 g
- High head and neck loading on the passenger dummy
- Vehicle has one load path, the longitudinals are located in the part 581 zone and they are in agreement with US voluntary agreement.
- Forces on row 3 are lower and forces on row 4 are higher compared to the previous test at BASt
- However, the vehicle will pass the metric but is close to fail

SUPERMINI 1 FWDB 56 KM/H (2) @ BAST

FWDB Supermini 1

Test Date	28/02/2012
Location	BASt
Topic	Full Width test
Test Number	FM04C3FW
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:		Barrier:	Full Width
Brand/type	Supermini 1		150 mm 0.34 MPa
Impact side:	Front		150 mm 1.71 MPa
Speed:	56 km/h		Segmented
Overlap:	100%	Impact accuracy	18 mm left 2 mm up
Test mass:	1300 kg	LCW ground clearance	80 mm
Dummy:	LHS - Hybrid III 50th RHS - Hybrid III 5th	LCW / barrier dimensions	2000 mm wide 750 mm high

Test objectives:

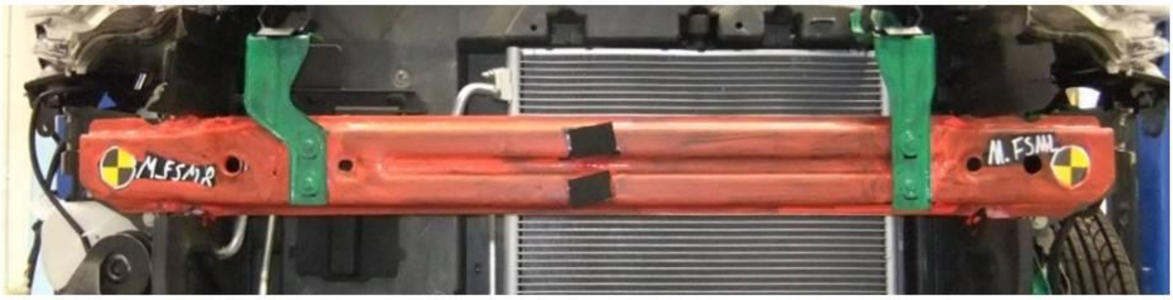
Test parameters

- Vehicle data: Supermini 1, LHD
- Engine / Transmission: 1.4 l diesel / 5 gear
- Test speed: 56.02 km/h
- Test weight: F 759 kg / R 541 kg Total 1300 kg
- Test impact accuracy: 18 mm left, 2 mm up

- Test vehicle status:
  - Not raised (references see next slides)

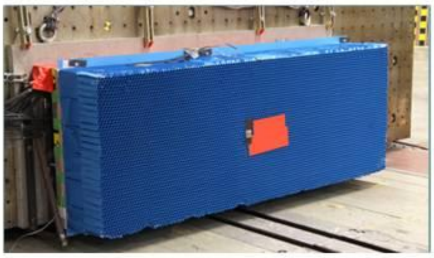
Car hight

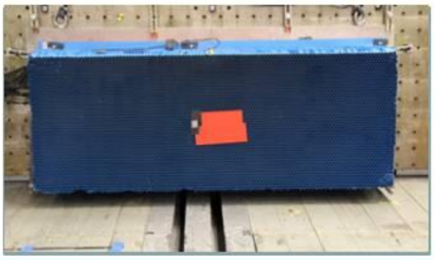
Ride heights (wing edge to floor distance) [mm]		
	Left side	Right side
Front	648	653
Rear	638	643

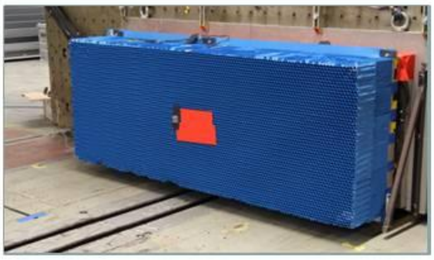


Pre-test Pictures

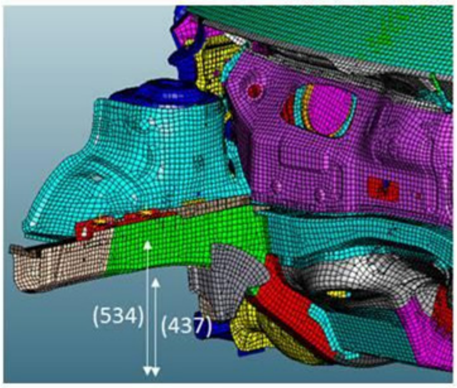
Pre-test Pictures
Barrier

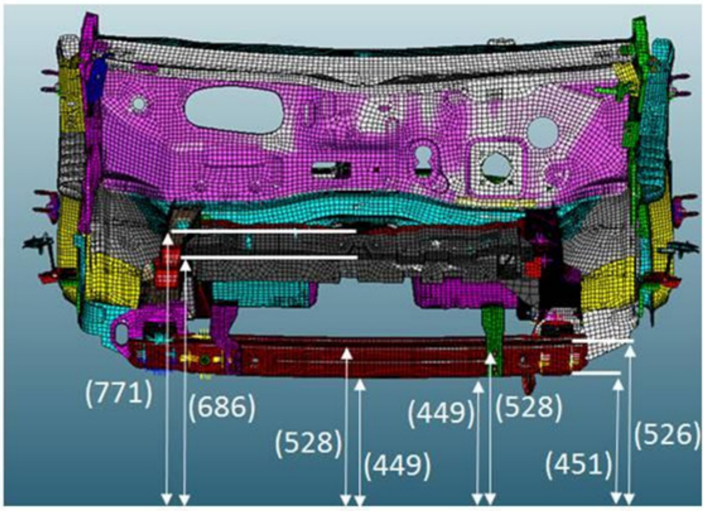




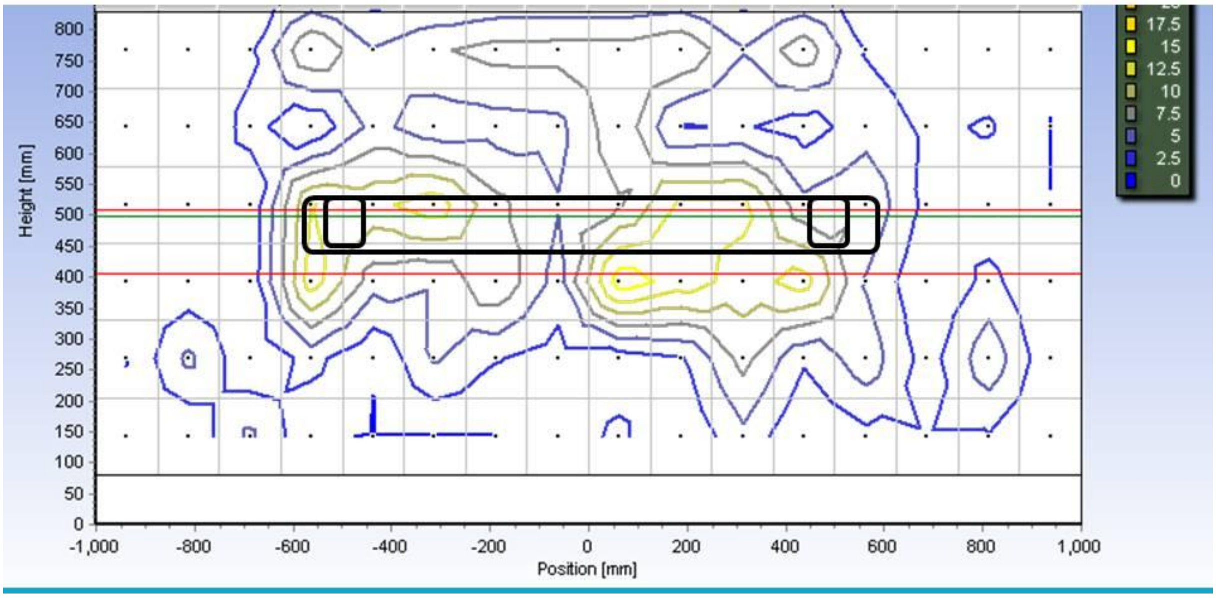


Supermini 1 front end structure





Vehicle Structure with LCW



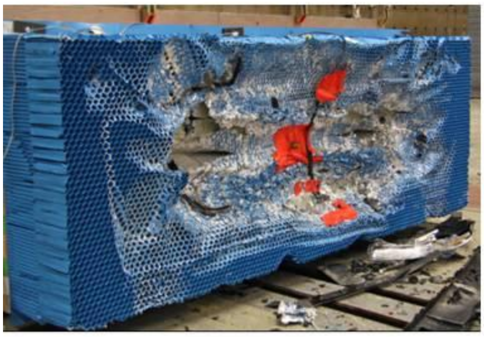
LCW Forces at 40 ms

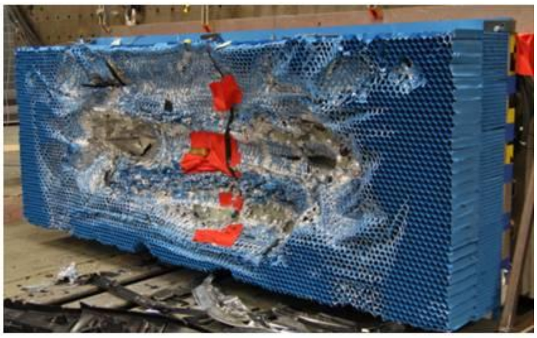
40.00 ms	-687.50	-562.50	-437.50	-312.50	-187.50	-62.50	62.50	187.50	312.50	437.50	562.50	687.50	812.50	937.50	Sum Rows
1017.50 [mm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
892.50 [mm]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
767.50 [mm]	1.97	9.90	5.13	7.16	8.44	8.51	8.49	9.83	5.15	9.09	2.30	0.99	0.76	0.15	79.52
642.50 [mm]	3.34	0.41	5.86	3.38	3.94	4.26	9.39	2.29	2.78	1.33	3.92	2.01	2.76	-0.02	45.93
517.50 [mm]	0.55	12.57	11.70	13.98	8.16	5.14	7.19	13.04	13.26	5.65	7.15	1.74	0.66	0.01	103.25
392.50 [mm]	0.56	13.86	6.03	5.24	9.75	4.08	16.52	13.86	11.36	13.52	4.75	0.22	3.24	0.08	104.10
267.50 [mm]	0.34	3.36	0.08	5.30	2.67	1.22	0.99	2.11	8.39	2.85	6.57	1.30	6.74	0.43	47.92
142.50 [mm]	5.52	0.21	-0.09	-0.07	-0.03	1.12	3.03	0.05	4.36	-0.01	1.86	2.36	2.35	0.11	21.20
Sum Columns	12.28	40.31	28.71	34.99	32.93	24.33	45.61	41.18	45.30	32.43	26.55	8.62	16.51	0.76	401.92

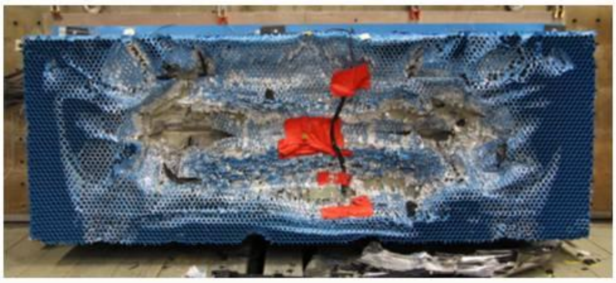
Post-test Pictures
Vehicle 1

b

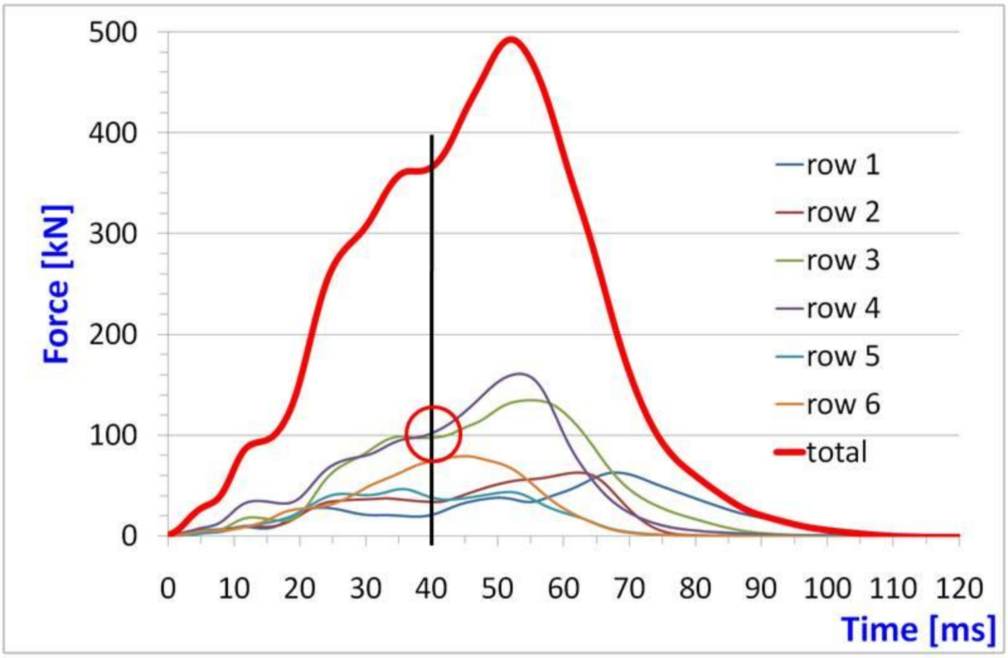
Post-test Pictures
Barrier





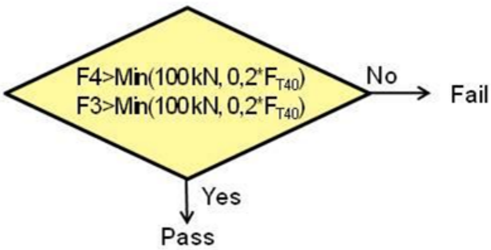


Plots: Row forces over time

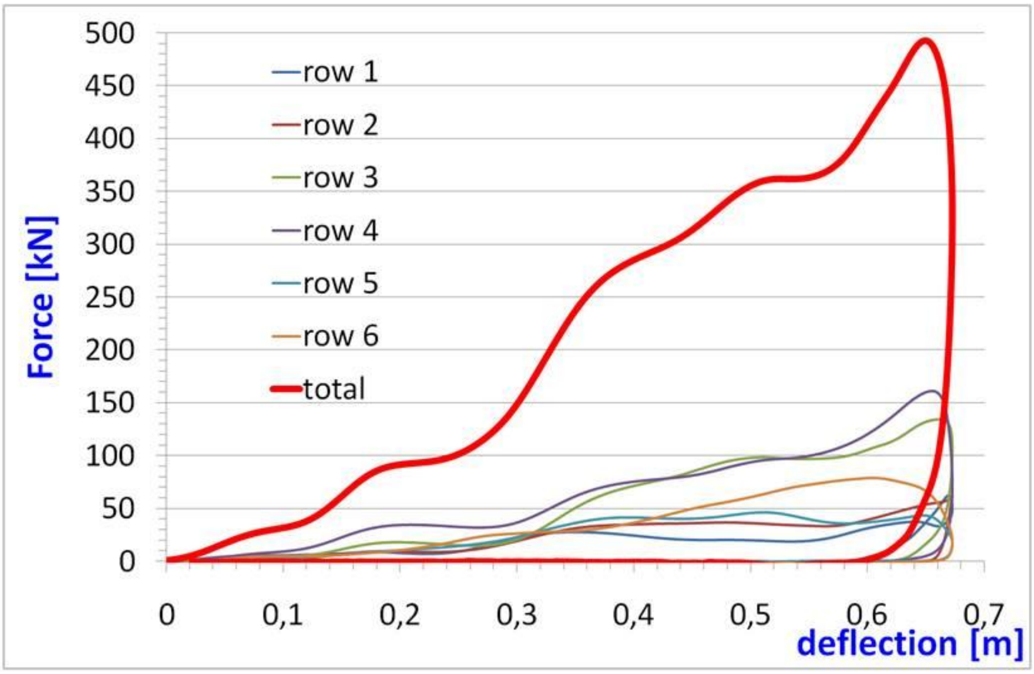


Metrics evaluation

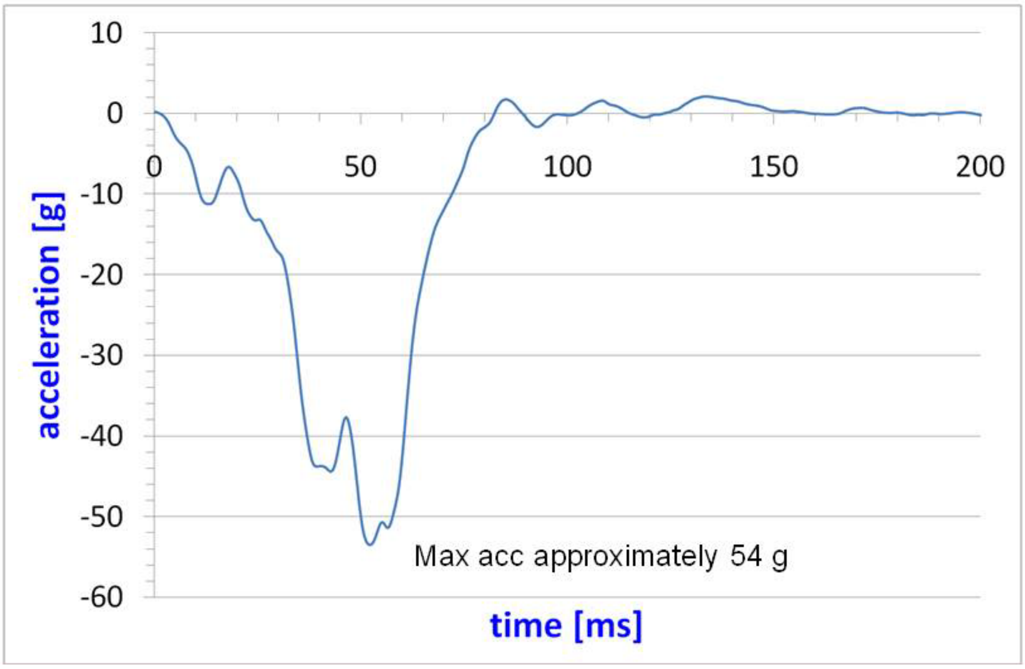
	Supermini 1 FWDB, FM04C3FW		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	104	80,4	OK
F4 > MIN[100, 0.2Ft40]	103	80,4	OK
Global	OK		



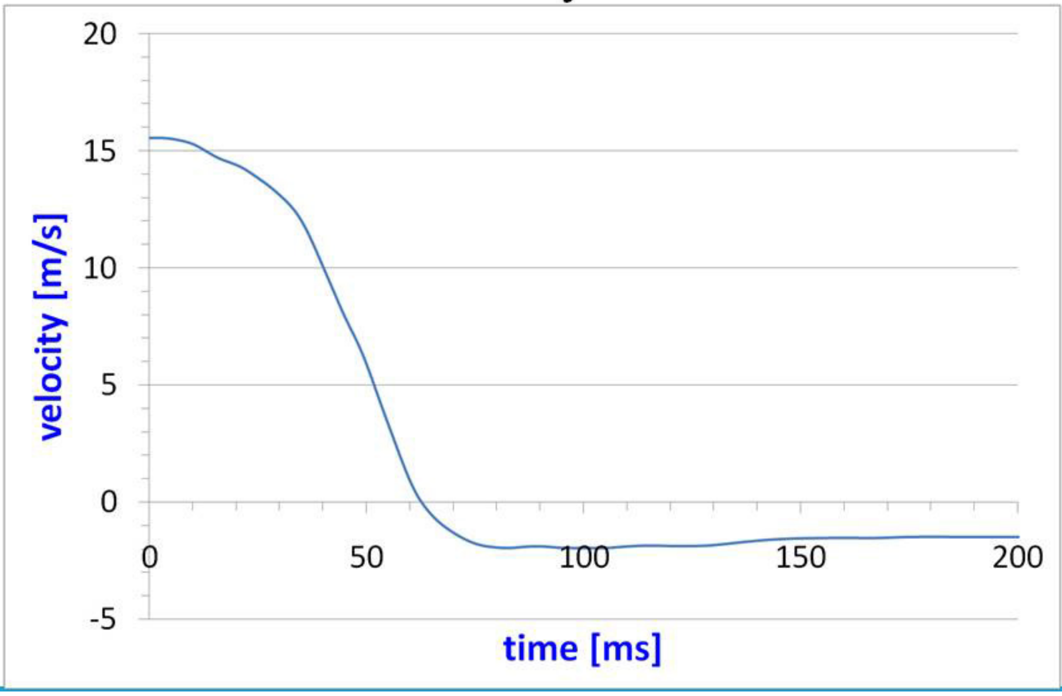
Plot: Row forces over deflection



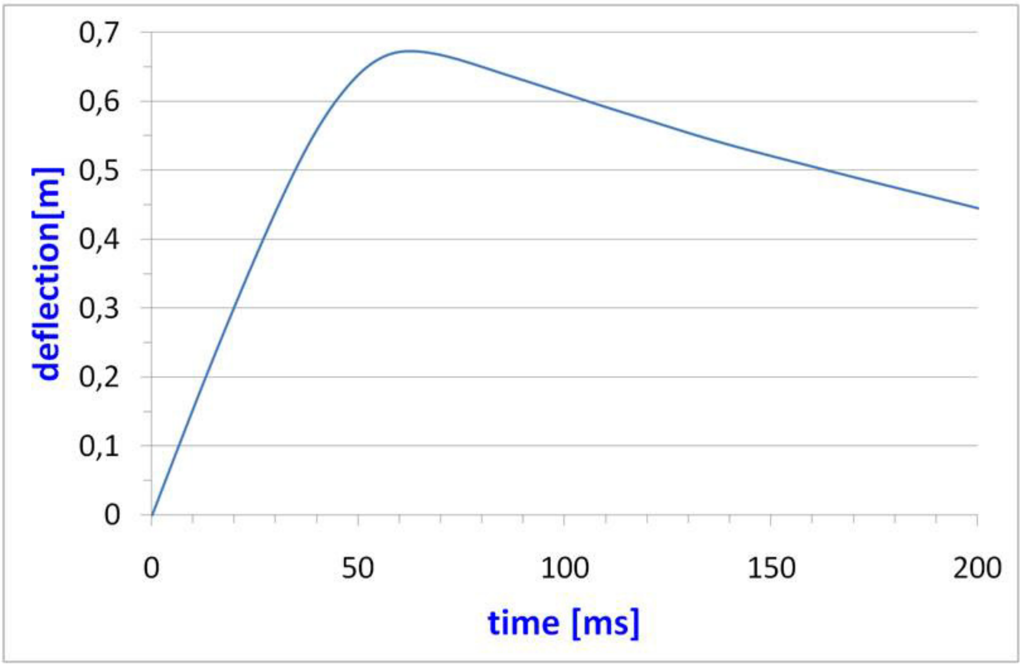
Plot: Vehicle acceleration (a+b pillar)



Plot: Velocity over time



Plot: Deflection over time



Dummy values FW Test

Criterion	Driver SP 1 (H3)				Co-Driver SP 3 (HF)			
Head & Neck			4.000	*			0.000	*
Head								
HIC 36	545.85				1089.92			
Acceleration Resultant	65.76	g	4.000	*	88.45			
3ms cumulative	63.75	g			87.33	g		
Neck								
Shear Force Fx+	0.77	kN	4.000	*	0.15	kN	0.000	*
Shear Force Fx-	-0.37	kN	4.000	*	-0.30	kN	0.000	*
Tensile Force Fz+	1.56	kN	4.000	*	1.25	kN	0.000	*
Extension My-	-14.17	Nm	4.000	*	-48.05	Nm		
Chest			4.000	*				
Deflection	-0.08	mm	4.000	*	-24.94	mm		
VC max	0.27	m/s	4.000	*	0.12	m/s		
belt at upper diagonal belt Force	5.44	kN			4.52	kN		
Femur & Knee			0.000	*				
Left								
Femur Force Fz-	-0.29	kN	4.000	*				
Knee Slider Displacement	-0.40	mm	4.000	*				
Right								
Femur Force Fz-	-20.90	kN	0.000	*				
Knee Slider Displacement	-0.51	mm	4.000	*				

Tibia			1.955	*		
Left						
Compression Upper Fz-	-2.64	kN	3.572	*	-0.75	kN
Compression Lower Fz-	-3.16	kN	3.229	*	-1.00	kN
Tibia Index Upper	0.86		1.955	*	0.80	
Tibia Index Lower	0.29		4.000	*	0.55	
Right						
Compression Upper Fz-	-1.68	kN	4.000	*	-0.70	kN
Compression Lower Fz-	-2.46	kN	3.696	*	-0.93	kN
Tibia Index Upper	0.76		2.397	*	0.61	
Tibia Index Lower	0.51		3.509	*	0.35	
Sum			9.955			(0.000)

Rating without modifiers


Points
- * 4.000
- * 2.670 - 3.999
- * 1.330 - 2.669
- * 0.001 - 1.329
- * 0.000

Dummy values Euro NCAP Test

	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	44,93	4,000	42,97	4,000
HIC_{36}	350,03		333,44	
Resultant Acc. 3 msec exeedence - g	44,38		41,89	
Unstable airbag contact, Bottoming out or Hazardous deployment		0,000		0,000
Steering wheel displacement (-1) mm	-4	0,000		
Incorrect airbag deployment		0,000		0,000
Head Assessment		4,000		4,000
NECK				
Shear level exceeded - kN	0,42	4,000	0,37	4,000
duration of exceedence - ms	0		0,00	
Tension level exceeded - kN	1,40	4,000	1,26	4,000
duration of exceedence - ms	0		0,00	
Extension - Nm	18,40	4,000	27,80	4,000
Neck Assessment		4,000		4,000
Head and Neck Assessment		4,000		4,000
CHEST				
Compression - mm	31,16	2,691	29,24	2,966
Viscous criterion - m/s	0,13	4,000	0,11	4,000
Steering wheel contact (-1)		0,000		
A-Pillar displacement (-2) mm	-24	0,000		
Unstable passenger compartment (-1)		0,000		
Shoulder belt load - kN	5,33		4,98	
Chest Incorrect Airbag Deployment Modifier		0,000		0,000
Chest Assessment		2,691		2,966
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0,0	4,000	0,0	4,000
Left Femur Compression level exceeded - kN	0,21	4,000	0,1	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Left Knee, Femur and Pelvis Assessment		4,000		4,000
Right Knee Slide - mm	0,0	4,000	0,0	4,000
Right Femur Compression level exceeded - kN	0,16	4,000	0,2	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Right Knee, Femur and Pelvis Assessment		4,000		4,000


Driver


Passenger

	Driver		Passenger	
Knee, Femur and Pelvis assessment		4,000		4,000
LOWER LEG				
Left compression - kN	2,14	3,907	1,55	4,000
Left Upper Tibia Index	0,47	3,689	0,38	4,000
Left Lower Tibia Index	0,26	4,000	0,23	4,000
Brake pedal vertical (-1) mm	-49	0,000		
Left Lower Leg assessment		3,689		4,000
Right compression - kN	0,92	4,000	1,42	4,000
Right Upper Tibia Index	0,42	3,911	0,39	4,000
Right Lower Tibia Index	0,29	4,000	0,22	4,000
Brake pedal vertical (-1) mm	-49	0,000		
Right Lower Leg assessment		3,911		4,000
FOOT and ANKLE				
Clutch pedal horizontal displacement - mm	-96	4,000		
Footwell Rupture (-1)		0,000		
Pedal Blocking (-1)	0	0,000		
Foot and Ankle assessment		4,000		
Lower Leg, Foot and Ankle assessment		3,689		4,000
SUMMARY				
Head and Neck assessment		4,000		4,000
Chest assessment		2,691		2,966
Knee, Femur and Pelvis assessment		4,000		4,000
Lower Leg, Foot and Ankle Assessment		3,689		4,000
TOTAL		14,380		14,966

TOTAL FRONTAL **14,380**

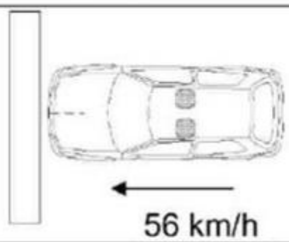
Conclusions

- Supermini 1 test with 56 km/h FWDB
- Max vehicle acceleration: 54 g
- High dummy values for the HIII 5th Dummy on front seat passenger side (head and neck)
- Vehicle has one load path, the longitudinals are located in the part 581 zone and they are in agreement with US voluntary agreement.
- According to the LCW forces calculated, the Vehicle passes the FWDB metric

SUPERMINI 1 FWDB 56 KM/H (3) @ FIAT

FWDB Supermini 1

Test Date	10/11/2011
Location	FIAT Safety Center
Topic	Full Width test
Mass Ratio	N/A
Test Number	17459
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:	Small car	Barrier:	Full Width
Brand/type	Supermini 1		150 mm 0.34 MPa
Impact side:	Front		150 mm 1.71 MPa
Speed:	56.39 km/h		Segmented
Overlap:	100%	Impact accuracy	10 mm left 0 mm
Test mass:	1289 kg	LCW ground clearance	80 mm
Dummy:	LHS - Hybrid III 50th RHS - Hybrid III 5th	LCW / barrier dimensions	2 m wide 0.75 m high

Test objectives:

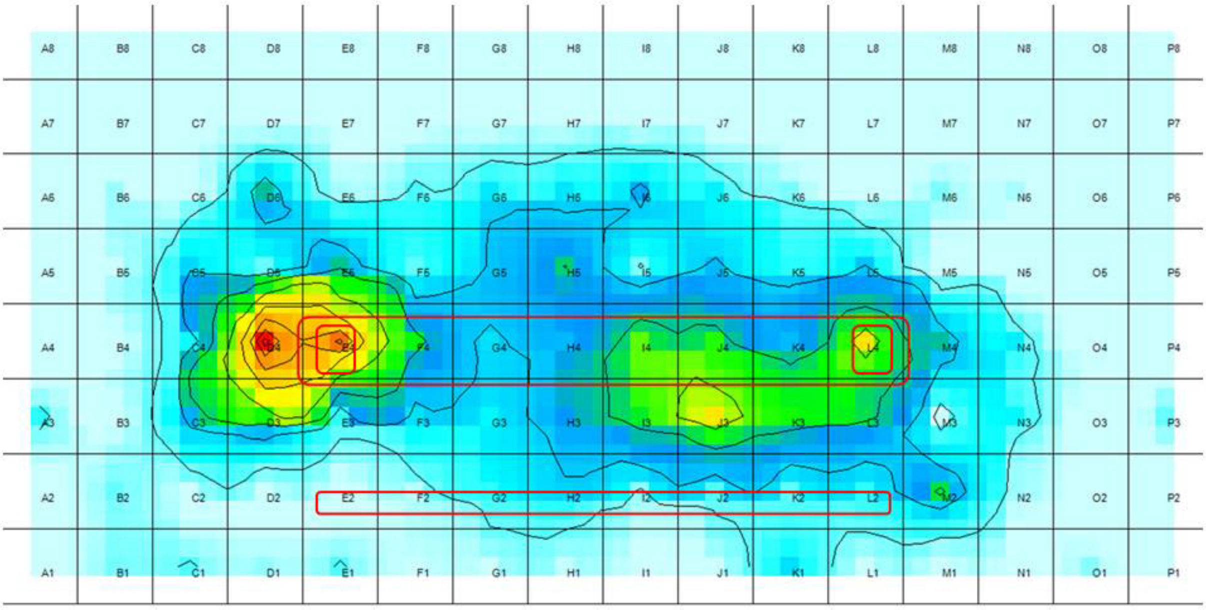
Test parameters

- Vehicle data: **Supermini 1 LHD**
- Engine / Transmission: 1.4 HDi / Manual
- Test speed: 56.39 kph
- Test weight: F 755 kg / R 534 kg Total 1289 kg
- Test impact accuracy: 10mm left, 0mm up
- Test vehicle status:
  - Standard ride heights:
  - Fender height R F 647
    Fender height L F 649
    Fender height R R 616
    Fender height L R 620

Pre-test Pictures
Vehicle 1

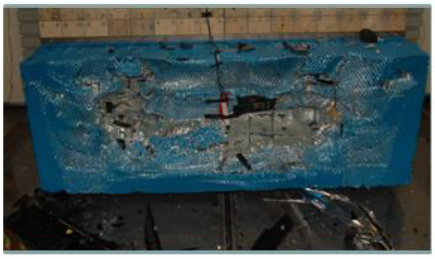
Pre-test Pictures
Barrier


Alignment of Vehicle Structure with LCW



Post-test Pictures
Vehicle 1

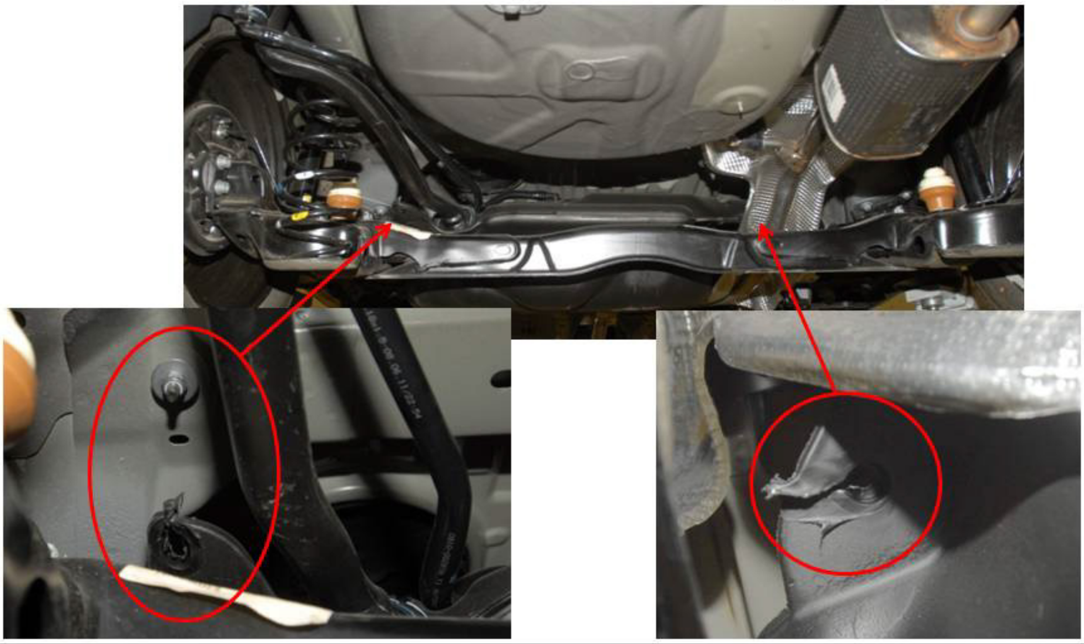
Post-test Pictures
Barrier



Additional pictures (1/2)

Separation between crossmember and CB/longitudinal

Additional pictures (2/2)

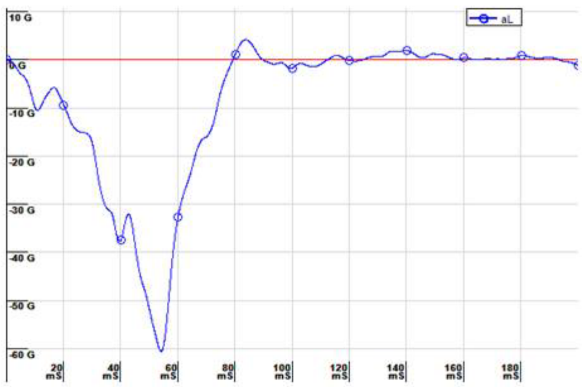


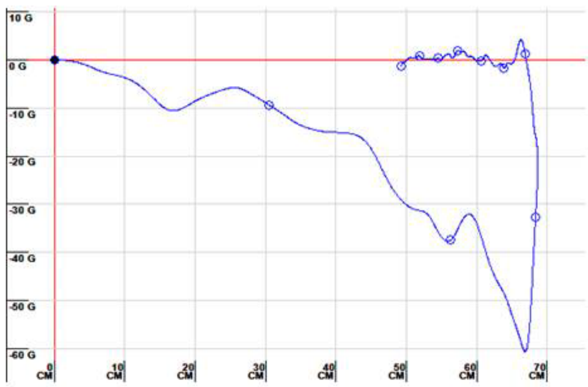
Failure of rear fuel tank fixages

Static measurements

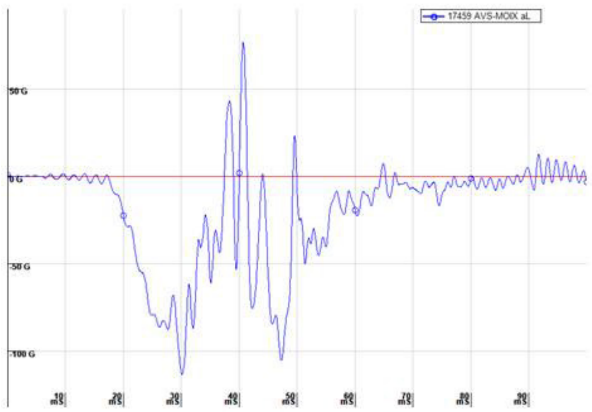
Frontal Impact	Rearw. Steering wheel displacment	Upward Steering wheel displacement	Lateral Steering wheel displacement	Rearw. A pillar displacement	Rearward pedal fixation displacement
Remarks	(mm)	(mm)	(mm)	(mm)	(mm)
FWDB - 56kph - 17459	-36	-72	0	5	35
	Occupant compartment stability	Footwell Ruptures	Rearw. Pedals displacement	Upward. Pedals displacement	G max SAE 60
			(mm)	(mm)	(g)
FWDB - 56kph - 17459	Yes	No	20 (accel)	-22 (accel)	61

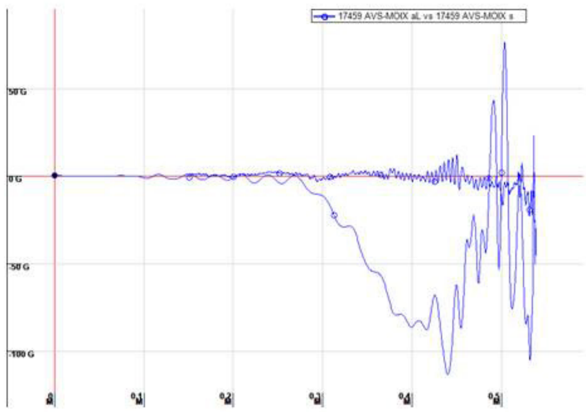
Car Accelerations
vs.
Time Displacement





Engine acceleration
vs.
Time Displacement





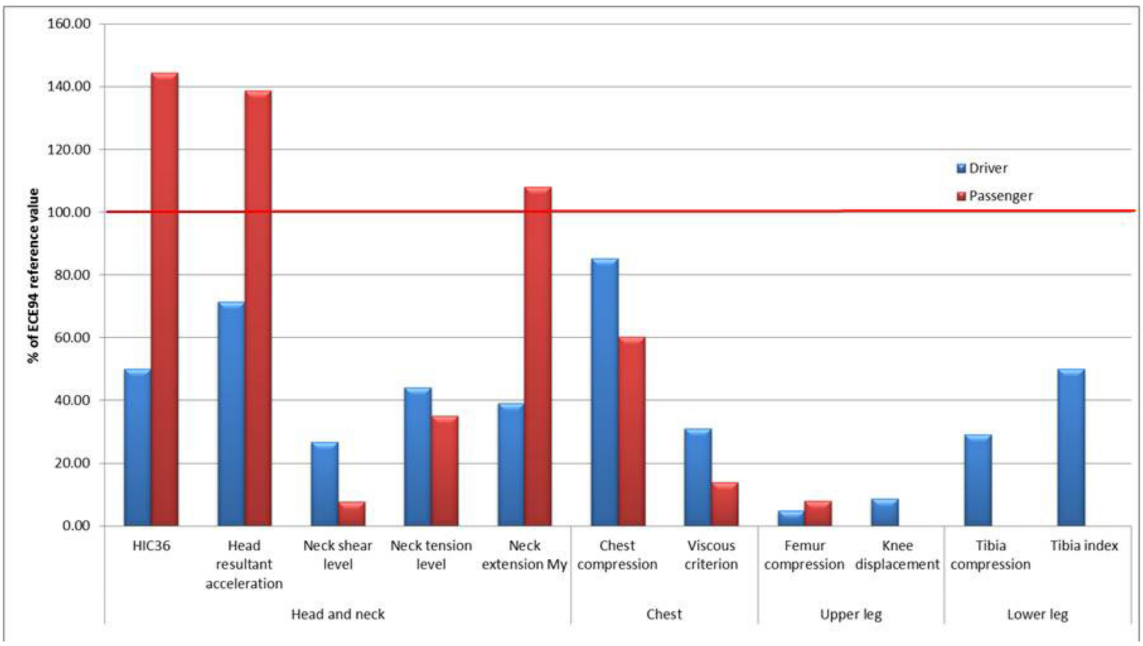
Dummy criteria comparison. - Standard FIMCAR database output

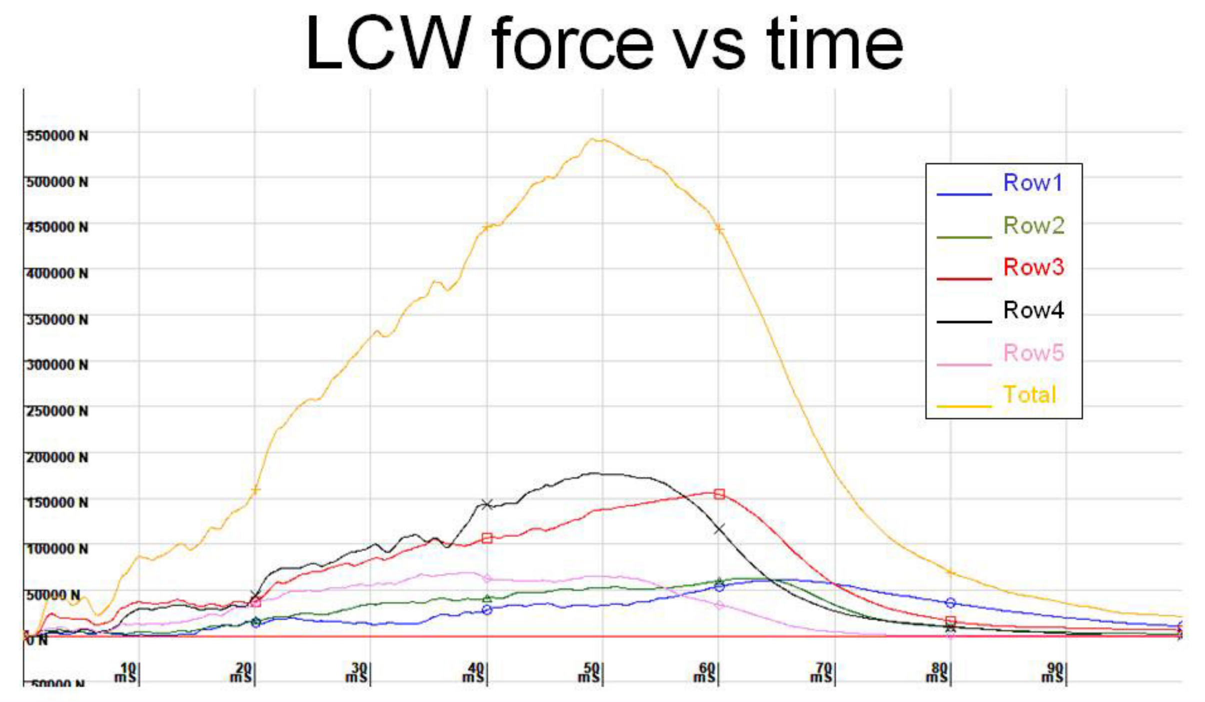
	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	57.20	4.000	110.94	0.000
HIC_{36}	502.24		1443.94	
Resultant Acc. 3 msec exeedence - g	55.45		104.78	
Head Assessment		4.000		0.000
NECK				
Shear level exceeded - kN	0.83	4.000	0.24	4.000
duration of exceedence - ms	0		0.00	
Tension level exceeded - kN	1.48	4.000	1.18	4.000
duration of exceedence - ms	0		0.00	
Extension - Nm	22.37	4.000	81.57	0.000
Neck Assessment		4.000		0.000
Head and Neck Assessment		4.000		0.000
CHEST				
Compression - mm	42.80	1.057	30.20	2.829
Viscous criterion - m/s	0.31	4.000	0.14	4.000
Shoulder belt load - kN	5.51		4.80	
Chest Assessment		1.057		2.829
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	1.3	4.000	0.0	4.000
Left Femur Compression level exceeded - kN	0.24	4.000	0.8	4.000
duration of exceedence - ms	0		0.0	
Left Knee, Femur and Pelvis Assessment		4.000		4.000
Right Knee Slide - mm	1.2	4.000	0.0	4.000
Right Femur Compression level exceeded - kN	0.50	4.000	0.2	4.000
duration of exceedence - ms	0		0.0	
Right Knee, Femur and Pelvis Assessment		4.000		4.000
Knee, Femur and Pelvis assessment		4.000		4.000

	Driver	Points	Passenger	Points
LOWER LEG				
Left compression - kN	2.34	3.773	0.00	4.000
Left Upper Tibia Index	0.85	2.889	0.00	4.000
Left Lower Tibia Index	0.35	4.000	0.00	4.000
pedal vertical (-1) mm	0	0.000		
Left Lower Leg assessment		2.889		4.000
Right compression - kN	2.33	3.780	0.00	4.000
Right Upper Tibia Index	0.59	3.158	0.00	4.000
Right Lower Tibia Index	0.44	3.822	0.00	4.000
pedal vertical (-1) mm	0	0.000		
Right Lower Leg assessment		3.158		4.000
FOOT and ANKLE				
pedal horizontal displacement - mm	0	4.000		
Footwell Rupture (-1)		0.000		
Pedal Blocking (-1)	0	0.000		
Foot and Ankle assessment		4.000		
Lower Leg, Foot and Ankle assessment		2.889		4.000
SUMMARY				
Head and Neck assessment		4.000		0.000
Chest assessment		1.057		2.829
Knee, Femur and Pelvis assessment		4.000		4.000
Lower Leg, Foot and Ankle Assessment		2.889		4.000
TOTAL		11.946		10.829

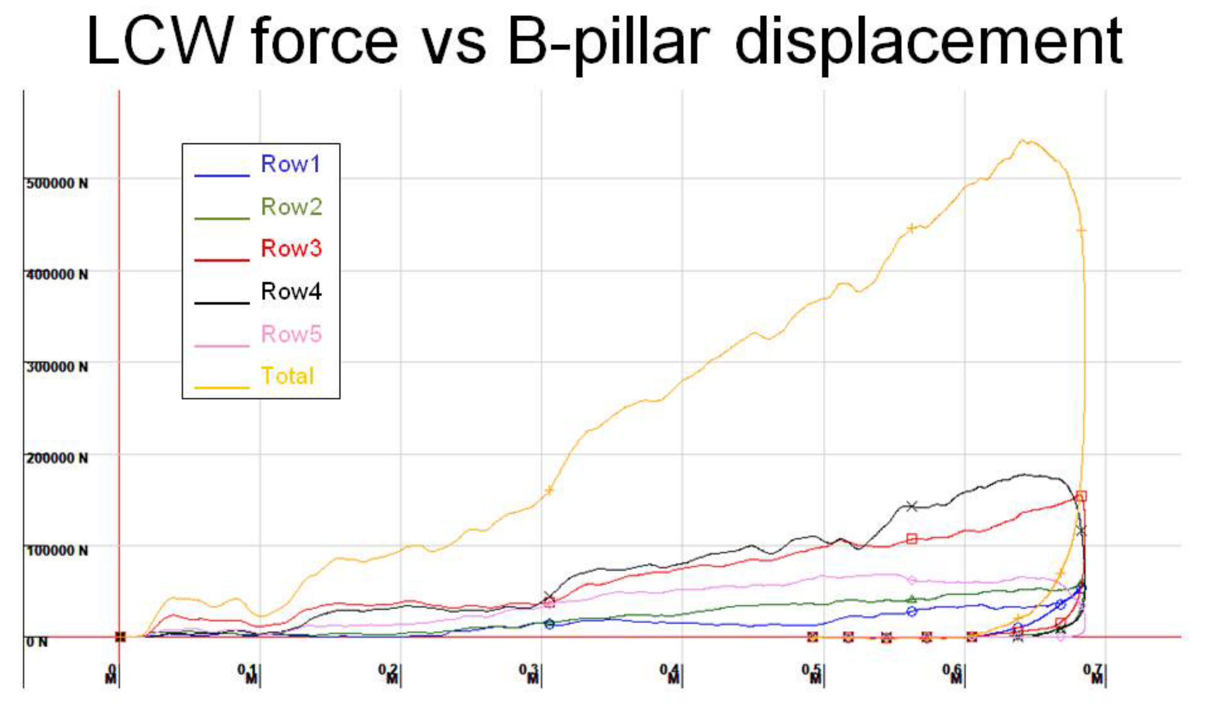
Restraint	Time-to-fire (movie analysis)
Retractor	19 ms
DAB	29 ms
PAB	39 ms

Dummy Criteria Comparison - % of Reference Value (Reg 94)





LCW force vs time
550000 N
500000 N
450000 N
400000 N
350000 N
300000 N
250000 N
200000 N
150000 N
100000 N
50000 N
0 N
-50000 N
10 mS
20 mS
30 mS
40 mS
50 mS
60 mS
70 mS
80 mS
90 mS
Row1
Row2
Row3
Row4
Row5
Total



LCW force vs B-pillar displacement
500000 N
400000 N
300000 N
200000 N
100000 N
0 N
0 M
0.1 M
0.2 M
0.3 M
0.4 M
0.5 M
0.6 M
0.7 M
Row1
Row2
Row3
Row4
Row5
Total

Metrics evaluation

Method B(1) FWDB: up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	Supermini 1 FWDB	
	Value	OK/KO
Time at 400kN (ms)	37.8	NA
F3+F4 > 180 kN (kN)	221.1	OK
F3 > 85 kN (kN)	105.3	OK
F4 > 85 kN (kN)	115.8	OK
Global	OK	

Method B(2) FWDB: up to 40 ms → F3 > 75 kN AND F4 > 75 kN

	Supermini 1 FWDB	
	Value	OK/KO
Up to 40 ms, F3 > 75 kN (kN)	106.4	OK
Up to 40 ms, F4 > 75 kN (kN)	142.8	OK
Global	OK	

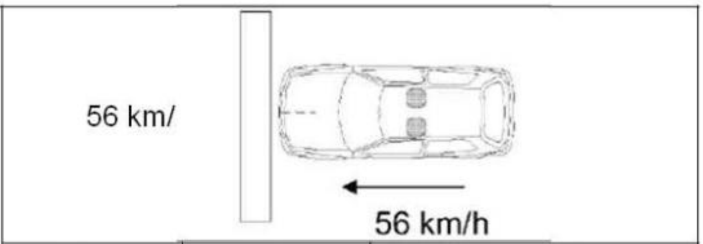
Upgrade1 FWDB: up to 40 ms → F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)]

	Supermini 1 FWDB		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	106.4	89.0	OK
F4 > MIN[100, 0.2Ft40]	142.8	89.0	OK
Global	OK		

SUPERMINI 1 FWDB 56 KM/H (LOWERED) @ IDIADA

Supermini 1 (lowered) FWDB test

Test Date	Nov. 14, 2011
Location	IDIADA
Topic	FWDB
Mass Ratio	NA
Test Number	114601FF
Test Protocol	FIMCAR



Vehicle 1:	Small family	Ride height measured at wheel arch:
Brand/type	Supermini 1	
Impact side:	Front	Front left: 618 mm
Speed:	56 km/h	Front right: 619 mm
Overlap:	100 %	
Test mass:	1337.0 kg	Rear left: 621 mm
Dummy:	LHS - Hybrid III 50th RHS - Hybrid III 50th	Rear right: 621 mm

Test objective: Car to FWDB test with lowered vehicle, 37 mm to the nominal position.

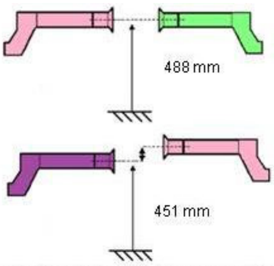
Full Frontal FWDB impact test on Supermini 1 (lowered)

Structural analysis

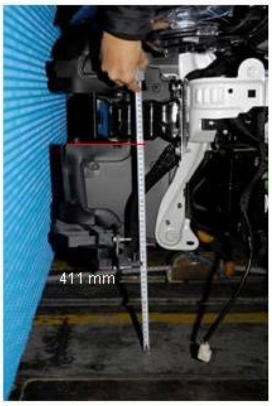
IDIADA test no. 114601FF

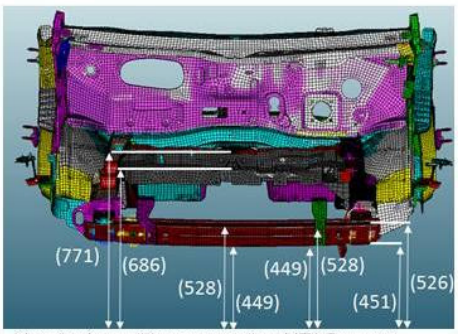
Vehicle: Supermini 1

Ground clearance: 413 mm to bumper beam CTR bottom



Lowered adjustment to achieve according UTAC report 488 – 451 = 37 mm





Nominal conditions according UTAC report

Full Frontal FWDB impact test on Supermini 1 (lowered)

Test conditions

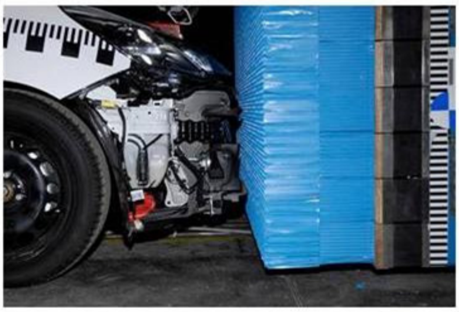
IDIADA test no. 114601FF

Vehicle: Supermini 1

Test Vehicle Mass: 1337.0 kg

Test velocity: 56.33 km/h

Ground clearance: 413 mm to bumper beam CTR bottom



SUMMARY		
Head and Neck assessment	4.000	1.850
Chest assessment	2.643	1.716
Knee, Femur and Pelvis assessment	4.000	4.000
Lower Leg, Foot and Ankle Assessment	2.844	3.644
TOTAL	13.487	11.210
Door Opening	0.00	
TOTAL FRONTAL	**10.410**	

Supermini 1 (lowered) FWDB Impact

Pre-Test photos

Supermini 1 (lowered) FWDB Impact
Static measurement results

- No door opening during the test.
- No door opening after the test.

Supermini 1

STATIC MEASUREMENTS

+ve= up,aft,left

STEERING WHEEL	
Fore/aft displacement - mm	-9
Vertical displacement - mm	-3
Lateral displacement - mm	4

A PILLAR	
Waistline displacement - mm	5

PEDAL DISPLACEMENTS	
Brake Vertical displacement - mm	-33
Brake Horizontal displacement - mm	15
Clutch Vertical displacement - mm	-32
Clutch Horizontal displacement - mm	6
Accel Vertical displacement - mm	-29
Accel Horizontal displacement - mm	20
MAXIMUM PEDAL MOVEMENT	
vertical displacement - mm	-29
horizontal displacement - mm	20

DOOR APERTURE	
Waist level collapse - mm	-6
Sill level collapse - mm	-1

Supermini 1 (lowered) FWDB Impact
Dummy results

Citroën C3

	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	78.52	4.000	81.67	1.850
HIC$_{36}$	648.33		822.06	
Resultant Acc. 3 msec exeedence - g	68.45		80.60	
Unstable airbag contact, Bottoming out or Hazardous deployment (-		0.000		0.000
Steering wheel displacement (-1) mm	4	0.000		
Incorrect airbag deployment		0.000		0.000
Head Assessment		4.000		1.850
NECK				
Shear level exceeded - kN	0.30	4.000	0.47	4.000
duration of exceedence - ms	0		0.00	
Tension level exceeded - kN	1.32	4.000	2.21	4.000
duration of exceedence - ms	0		0.00	
Extension - Nm	24.22	4.000	42.94	3.749
Neck Assessment		4.000		3.749
Head and Neck Assessment		4.000		1.850
CHEST				
Compression - mm	31.50	2.643	37.99	1.716
Viscous criterion - m/s	0.16	4.000	0.26	4.000
Steering wheel contact (-1)		0.000		
A-Pillar displacement (-2) mm	5	0.000		
Unstable passenger compartment (-1)		0.000		
Shoulder belt load - kN	0.00		0.00	
Chest Incorrect Airbag Deployment Modifier		0.000		0.000
Chest Assessment		2.643		1.716

KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	1.0	4.000	0.4	4.000
Left Femur Compression level exceeded - kN	0.23	4.000	0.2	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
Incorrect airbag deployment		0.000		0.000
Left Knee, Femur and Pelvis Assessment		4.000		4.000
Right Knee Slide - mm	0.4	4.000	0.1	4.000
Right Femur Compression level exceeded - kN	0.52	4.000	0.1	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
Incorrect airbag deployment		0.000		0.000
Right Knee, Femur and Pelvis Assessment		4.000		4.000
Knee, Femur and Pelvis assessment		4.000		4.000

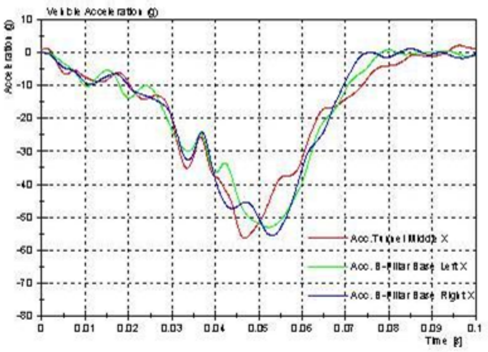
LOWER LEG				
Left compression - kN	2.86	3.427	2.06	3.960
Left Upper Tibia Index	0.58	3.200	0.44	3.822
Left Lower Tibia Index	0.66	2.844	0.28	4.000
pedal vertical (-1)mm	-29	0.000		
Left Lower Leg assessment		2.844		3.822
Right compression - kN	2.90	3.400	1.94	4.000
Right Upper Tibia Index	0.58	3.200	0.48	3.644
Right Lower Tibia Index	0.34	4.000	0.28	4.000
pedal vertical (-1)mm	-29	0.000		
Right Lower Leg assessment		3.200		3.644
FOOT and ANKLE				
pedal horizontal displacement - mm	20	4.000		
Footwell Rupture (-1)		0.000		
Pedal Blocking (-1)	-67	0.000		
Foot and Ankle assessment		4.000		
Lower Leg, Foot and Ankle assessment		2.844		3.644

Supermini 1 (lowered) FWDB Impact

Vehicle pulse

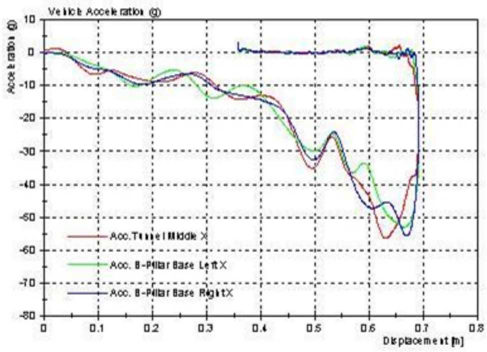
Time

B–Pillar Left side



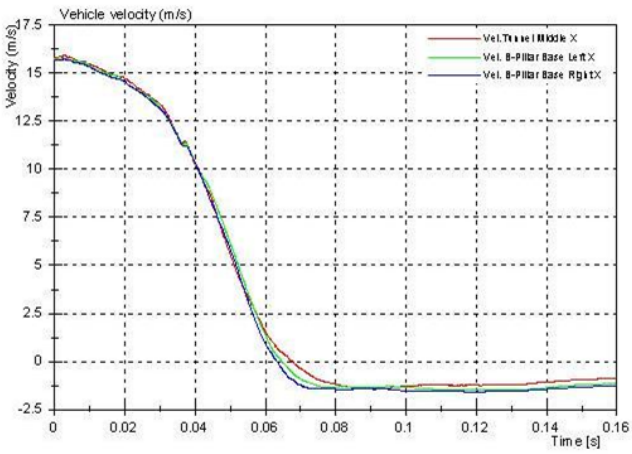
Displacement

B–Pillar Left side



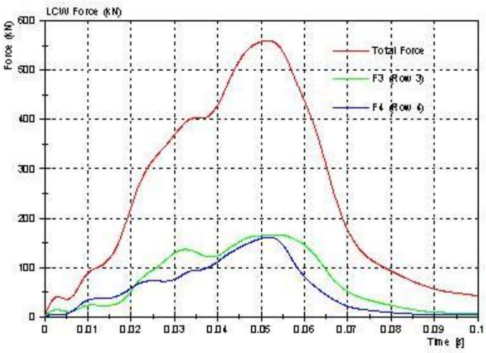
Supermini 1 (lowered) FWDB Impact

Vehicle velocity



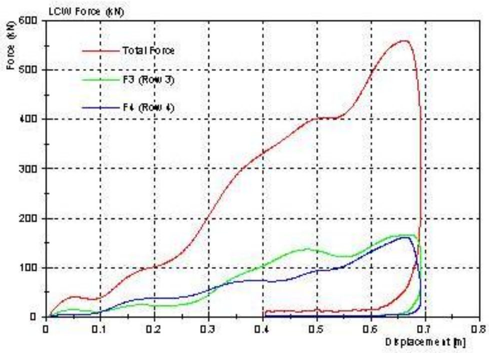
Supermini 1 (lowered) FWDB Impact
LCW Force

Time

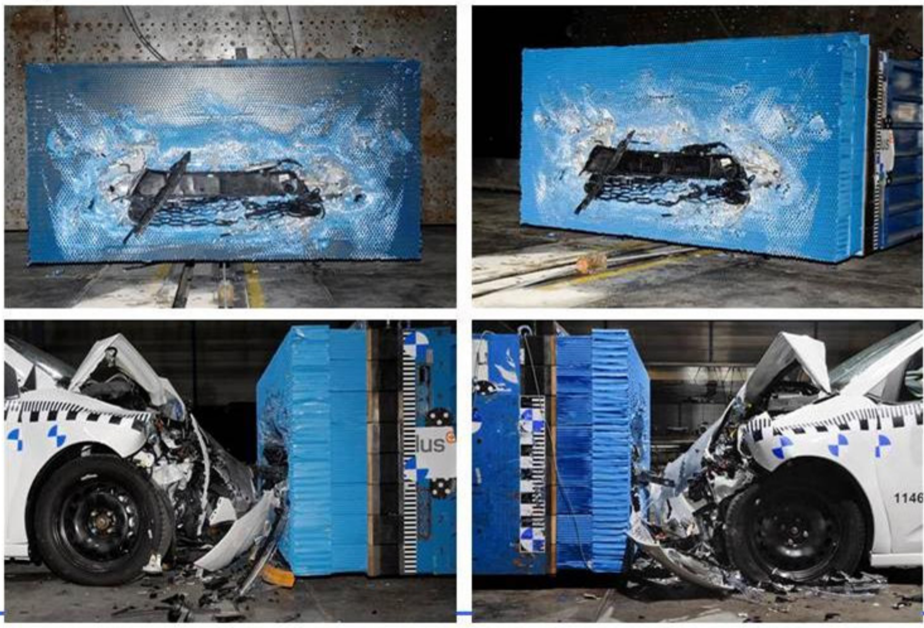


Displacement

B–Pillar Left side



Supermini 1 (lowered) FWDB Impact
Post-test photos



Supermini 1 (lowered) FWDB Impact
Metrics

- Metric 1

- Stage 1 Metric @ total LCW force 400 kN

F3+F4>[180 (160)] kN	F3+F4= 228.0 kN	PASS
F3>[85 (75)] kN	F3=135.8 kN	PASS
F4>[85 (75)] kN	F4=92.2 kN	PASS

Note: Limits in brackets are for vehicles for which the total LCW force is less than 400 kN

- Stage 2 (if stage 1 not met and eligibility met)

Metric up to time of 40 ms

F3>[100] kN	F3= 124.4 kN
F4>[100] kN	F4= 112.5 kN

- Metric 2 "upgrade"

Metric up to time of 40 ms

F3≥[MIN(100, 0.2xFT40) kN	F3=124.4 kN; 0.2xFT40=85.9 kN	PASS
F4≥[MIN(100, 0.2xFT40] kN	F4=112.5 kN; 0.2xFT40=85.9 kN	PASS

FT40=Maximum of total LCW force up to time of 40 ms

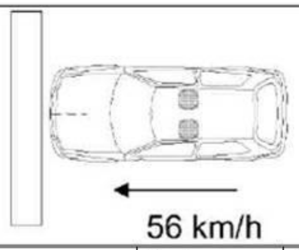
Supermini 1 (lowered) FWDB Impact
Conclusions

- Dummy injury bellow R94 limits
- The Supermini 1 (lowered) passes the FWDB Original an Upgrade Metrics

SUPERMINI 1 FWDB 56 KM/H (RAISED) @ PSA

FWDB Supermini 1 raised +39mm

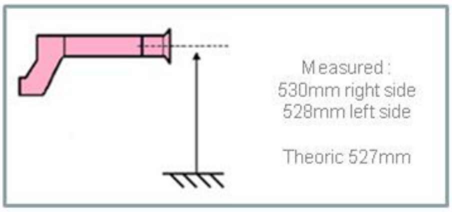
Test Date	31/10/2011
Location	TNO Safety Center
Topic	Full Width test
Test Number	F114202
Test Protocol	Draft FWDB protocol



Vehicle 1:	Small car	Barrier:	Full Width
Brand/type	Supermini 1, LHD		150 mm 0.34 MPa
Impact side:	Front		150 mm 1.71 MPa
Speed:	55.8 km/h		Segmented
Overlap:	100%	Impact accuracy	6mm below
Test mass:	1315 g		
Dummy:	Left - HIII 50th	LCW ground clearance	80 mm
	Right HIII 50th	LCW / barrier dimensions	2 m wide 1 m high

Test parameters

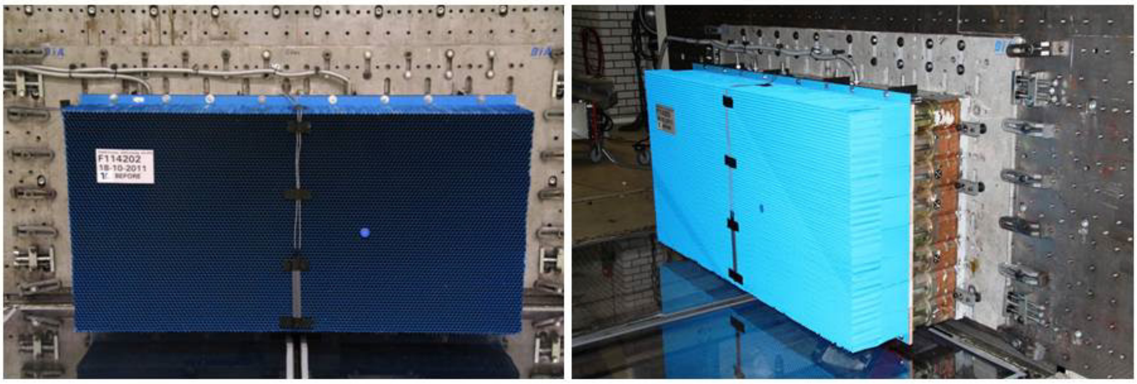
- **Vehicle data: Supermini 1**
- **Test number F114202**
- **Engine / Transmission: 1.4 HDi / Manual 5+R**
- **Test speed: 55.8 kph**
- **Test weight: F 787.5 kg / R 527.5 kg Total 1315 kg**
- **Test impact accuracy: 6mm below**
- **Test vehicle status:**
  - **Raised front and rear ride heights** ***+39mm***
  - **Fender height R F 685**
    Fender height L F 681
    Fender height R R 654
    Fender height L R 651



Pre-test Pictures
Vehicle 1 (raised +39mm)

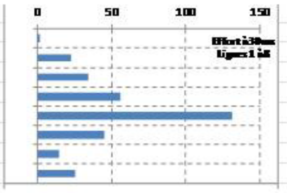
Pre-test Pictures
Barrier

FWDB Cellbond 2000x1000x300mm
2 stages of cells: **0.34MPa** / 1.7MPa

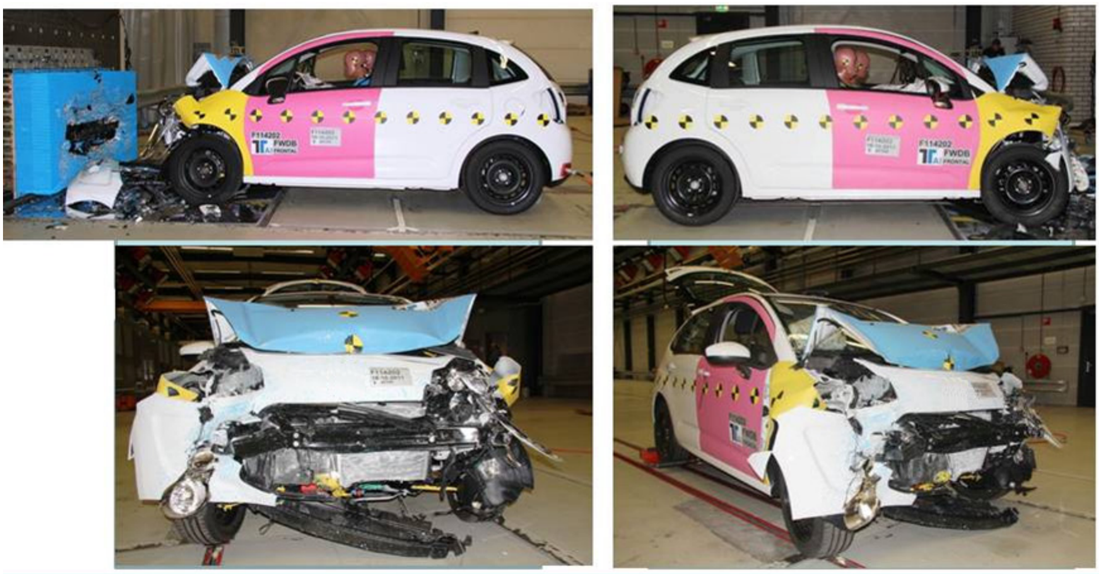


Alignment of Vehicle Structure with LCW

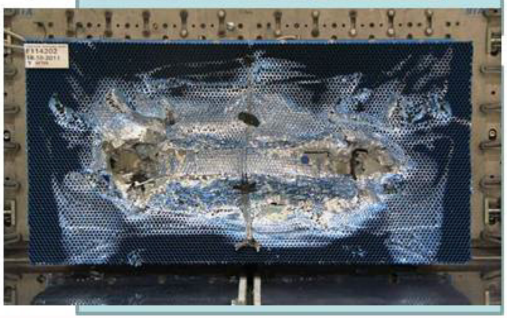
30 ms																	
-11	-58	-43	20	19	139	88	1307	258	16	-43	-13	-44	301	-23	-128	1%	2
30	-35	14	3480	-10	2288	266	5247	298	26	10218	-44	47	10	952	-68	7%	23
-34	-38	52	8139	575	4472	1584	4738	9940	313	3569	700	2	196	217	161	10%	35
-49	1	602	7398	1614	10005	1007	10041	3817	7187	3334	1465	5922	1027	2466	-106	17%	56
692	-3	3105	7688	27824	9764	5477	6500	9057	12355	21448	21736	4930	434	-5	366	40%	131
12	8	228	781	5148	2568	3163	6465	4362	4934	6436	8074	2371	-20	-65	381	14%	45
-163	-105	-21	-69	27	6261	-21	2519	2008	1476	2071	540	-5	6	-59	-60	4%	14
-99	-114	4796	-77	3140	66	1978	18	2837	3182	579	5538	-45	3635	-41	10	8%	25

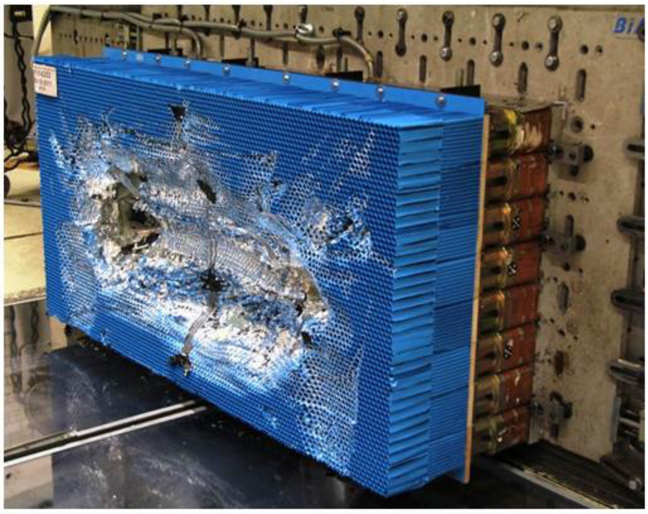


Post-test Pictures
Vehicle 1



Post-test Pictures
Barrier





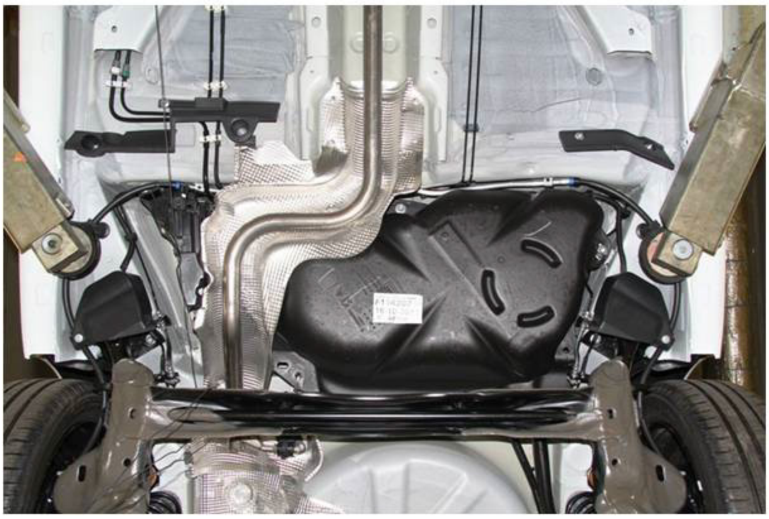
Additional pictures (1/3)

LEFT : Failure between front member and crash box, partial collapsing of the crash box
RIGHT : No failure between front member and crash box, no collapsing of the crash box (bending and side displacement), but beginning of failure on the front cross member (see orange mark)

Additional pictures (2/3)

Beginning of crushing of the 2 windscreen pillars, more important on right side
This appear between 60 and 65ms.

Additional pictures (2/3)



2 attachments of the rear fuel tank has been broken
No leakage observed.

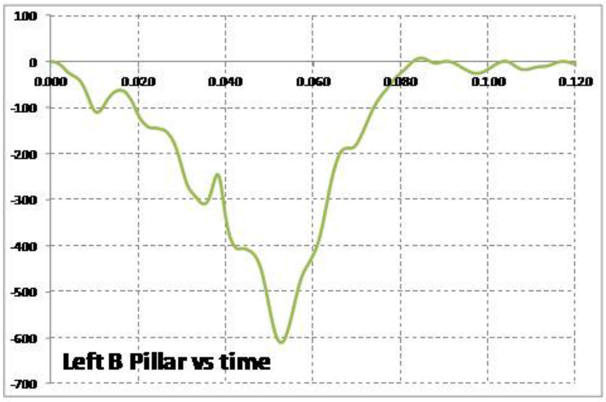
Static measurements

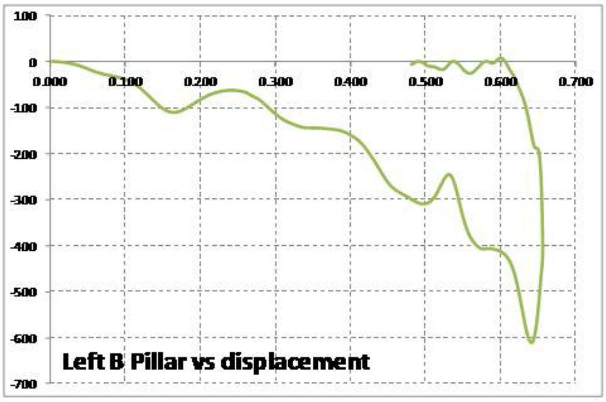
(raised +39mm)

FRONTAL IMPACT	Rearward steering wheel displacement (mm)	Upward steering wheel displacement (mm)	Lateral steering wheel displacement (mm)	Rearward A pillar displacement (mm)	
	-50	-30	-3	9	
	Occupant compartmernt stability	Footwell failures	Rearward pedals displacement (mm)	Upward pedals displacement (mm)	G max CFC60 (g)
	Yes	No	16	-23	62.3

Supermini 1 raised +39mm car accelerations vs.

Time / Displacement





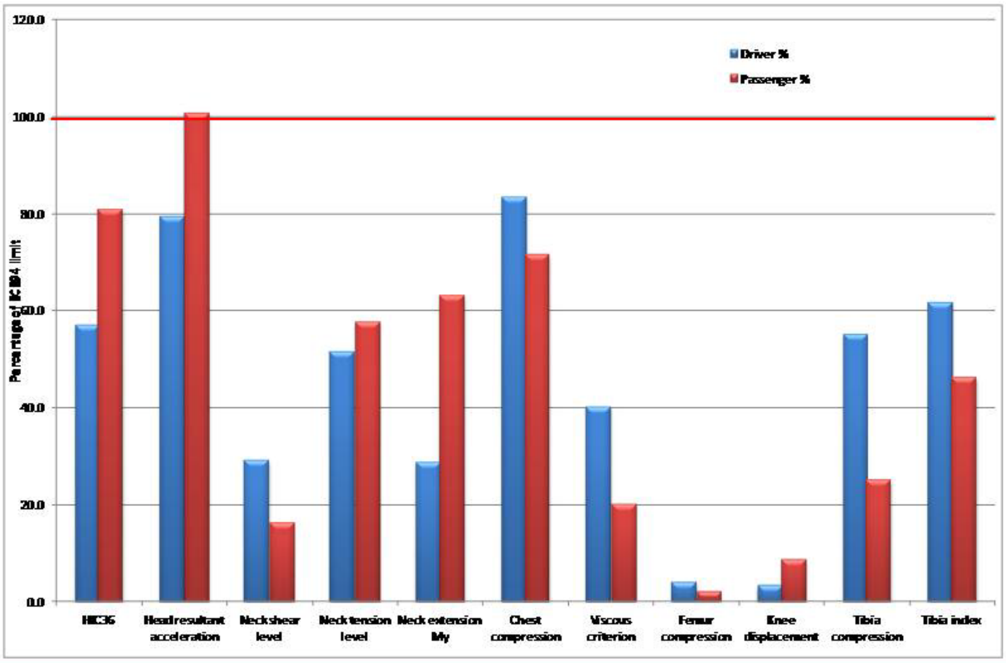
Dummy criteria comparison. - Standard FIMCAR database output

Raised vehicle	DRIVER		CO-DRIVER	
	Value	Points	Value	Points
HEAD				
HIC 36ms	570.00	4.000	808.00	2.194
Acceleration 3ms (g)	63.50	4.000	80.50	1.875
		4.000		1.875
NECK				
Shear Fx (kN)	0.87	4.000	0.49	4.000
Tension Fz (kN)	1.73	4.000	1.85	4.000
My Extension (N.m)	16.30	4.000	57.00	0.000
		4.000		0.000
CHEST				
Compression (mm)	41.70	1.186	35.80	2.029
Viscous criterion (m/s)	0.37	4.000	0.20	4.000
		1.186		2.029
KNEE & FEMUR				
Let Femur Compression (kN)	0.42	4.000	0.24	4.000
Let Knee Slide (mm)	0.49	4.000	1.26	4.000
		4.000		4.000
Right Femur Compression (kN)	0.40	4.000	0.10	4.000
Right Knee Slide (mm)	0.25	4.000	0.06	4.000
		4.000		4.000
INF MEMBERS				
Let Compression tibia Upper (kN)	2.15	3.900	1.98	4.000
Let compression tibiaLower (kN)	1.64	4.000	1.91	4.000
Let TI upper	0.37	4.000	0.60	3.111
Let TI lower	0.56	3.289	0.37	4.000
		3.289		3.111
Right compression tibia upper (kN)	3.07	3.287	1.57	4.000
Right compression tibia lower (kN)	4.39	2.407	1.79	4.000
Right TI upper	0.82	2.133	0.46	3.733
Right TI lower	0.41	3.956	0.29	4.000
		2.133		3.733

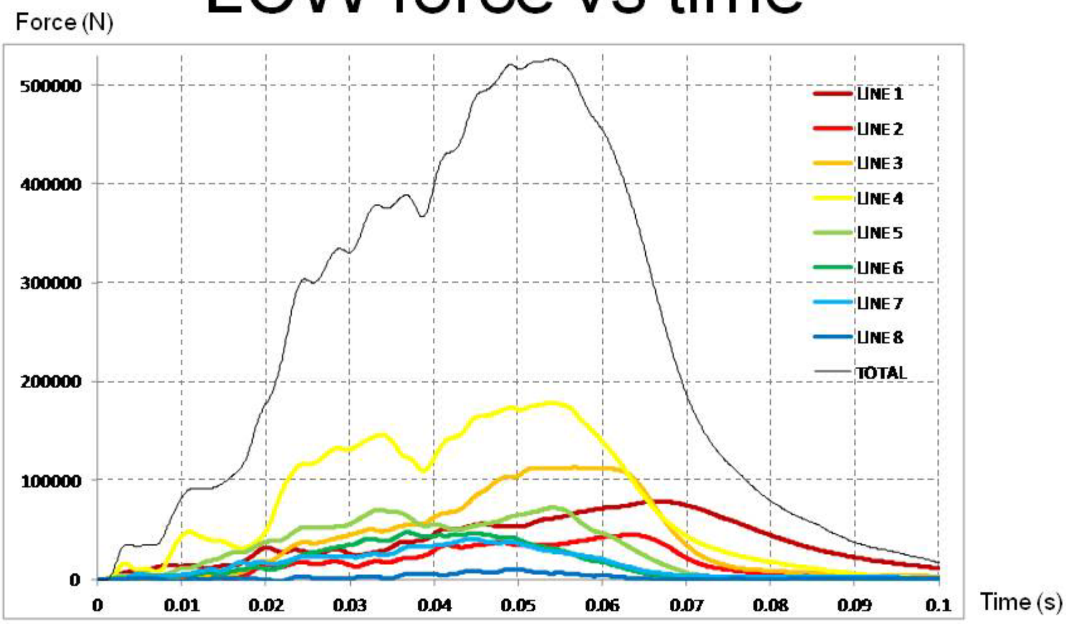
	DRIVER	CO-DRIVER
HEAD & NECK	4.000	0.000
CHEST	1.186	2.029
KNEE & FEMUR	4.000	4.000
INF MEMBERS	2.133	3.111
TOTAL	11.32	9.140

Restraint	Time-to-fire (movie analysis)
Retractor	18 ms
DAB	26 ms
PAB	39 ms

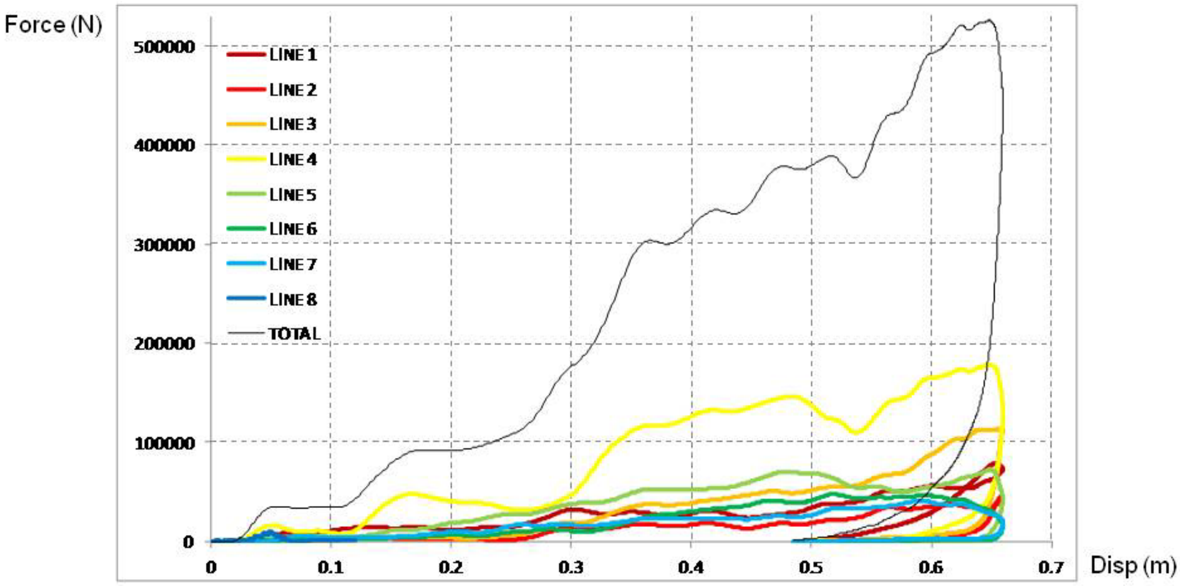
Dummy Criteria Comparison - % of Reference Value (Reg 94)



LCW force vs time



LCW force vs B-pillar displacement



Compatibility criteria (raised +39mm)

Method B(1) FWDB: up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	Supermini 1 FWDB raised	
	Value	OK/KO
Time at 400kN (ms)	40.0	NA
F3+F4 > 180 kN (kN)	185.7	OK
F3 > 85 kN (kN)	62.9	KO
F4 > 85 kN (kN)	122.8	OK
Global	KO	

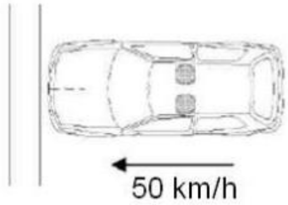
Method B(2) FWDB: up to 40 ms → F3 > 75 kN AND F4 > 75 kN

	Supermini 1 FWDB raised	
	Value	OK/KO
Up to 40 ms, F3 > 75 kN (kN)	62.9	KO
Up to 40 ms, F4 > 75 kN (kN)	122.8	OK
Global	KO	

Upgrade1 FWDB: up to 40 ms → F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)]

	Supermini 1 FWDB raised +39mm		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	62.9	79.7	KO
F4 > MIN[100, 0.2Ft40]	122.8	79.7	OK
Global	KO		

SUPERMINI 2 FWRB 50 KM/H @ IDIADA

Test Date Location Topic Mass Ratio Test Number Test Protocol	Jul. 18, 2011 IDIADA FWRB NA 112901FF FIMCAR	

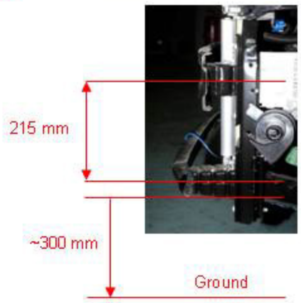
Vehicle 1: Brand/type Impact side: Speed: Overlap: Test mass: Dummy:	Super-mini Supermini 2 Front 50 km/h 100% 1159 kg LHS - HIII 50% RHS - HIII 5%	Ride height measured at wheel arch: Front left: 620 mm Front right: 623 mm Rear left: 614 mm Rear right: 624 mm

<u>Test object</u>

- **Vehicle 1 data: Supermini 2**
- **Engine / Transmission: 1.2 / Manual**
- **Test weight: F 648.5_kg / R 474.5_kg Total 1159_kg**

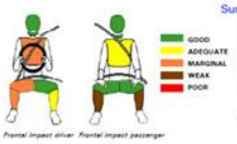
- **Test vehicle status:**
  Normal vehicle conditions
- **SEAS 215 mm below PEAS, SEAS well connected to the subframe which is 400 mm behind.**

Structure analysis



Dummy criteria comparison. - Standard FIMCAR database output

Supermini 2 FWRB



Summary.

Head and Neck Assessment	4.000
Chest Assessment	2.173
Knee, Femur and pelvis Assessment	1.938
Lower leg, Foot and Ankle Assessment	0.356

TBA: Modifiers to be assessed

Overall Frontal Assessment 8.467

Note: Score controlled by Driver results, Passenger HIII 5%tile can not be directly compared to the Euro NCAP result

Section	Item	Front impact driver. () Assessment	Value	Score	Front impact passenger. () Assessment	Value	Score
Head	Peak resultant.		76.41 g	(4.000)		73.97 g	(4.000)
	HIC_36		778.56	--		821.08	--
	Acc resultant (3 ms.)		75.33 g	--		72.31 g	--
	Head bottoming out. (-1)			TBA			TBA
	Unstable airbag contact. (-1)			TBA			TBA
	Steering wheel displacement. (-1)			TBA			
Head Assessment:		4.000			4.000		
Neck	Shear level exceed.		0.52 kN			0.73 kN	
	duration of exceedence		0.00 ms	(4.000)		0.00 ms	(4.000)
	Tension level exceed.		1.64 kN			0.78 kN	
	duration of exceedence		0.00 ms	(4.000)		0.00 ms	(4.000)
	Extension Nm.		-22.89 Nm	(4.000)		-16.71 Nm	(4.000)
Neck Assessment:		4.000			4.000		
Head and Neck Assessment:		4.000			4.000		
Chest	Compression		-34.79 mm	(2.173)		-30.49 mm	(2.787)
	Viscous criterion.		0.33 m/s	(4.000)		0.37 m/s	(4.000)
	Steering wheel contact.(-1)			TBA			
	A-Pillar displacement.(-2)			TBA			
	Unstable passenger compartment. (-1)			TBA			
Chest Assessment:		2.173			2.787		
Knee, Femur and Pelvis.	Left knee slide.		-0.49 mm	(4.000)		-0.01 mm	(4.000)
	Left femur compresion exceed.		-0.39 kN			-1.07 kN	
	duration of exceedence		0.00 ms	(4.000)		0.00 ms	(4.000)
	Variable contact(-1)			TBA			TBA
	Concentrate loading.(-1)			TBA			TBA
Left Knee, Femur and Pelvis Assessment:		4.000			4.000		
	Right knee slide.		-10.64 mm	(1.938)		0.00 mm	(4.000)
	Right femur compresion exceed.		-6.29 kN			-0.43 kN	
	duration of exceedence		0.00 ms	(2.092)		0.00 ms	(4.000)
	Variable contact(-1)			TBA			TBA
	Concentrate loading.(-1)			TBA			TBA
Right Knee, Femur and Pelvis Assessment:		1.938			4.000		
Lower leg. Left.	Left compresion.		-2.04 kN	(3.973)		-1.89 kN	(4.000)
	Left upper tibia index.		0.46	(3.733)		1.03	(1.200)
	Left lower tibia index.		0.24	(4.000)		1.11	(0.844)
	Pedal vertical (-1)			TBA			
Left Lower Leg Assessment:		3.733			0.844		
Right.	Right compresion.		-5.90 kN	(1.400)		-2.37 kN	(3.753)
	Right upper tibia index.		0.51	(3.511)		1.22	(0.356)
	Right lower tibia index.		0.40	(4.000)		0.84	(2.044)
	Pedal vertical (-1)			TBA			
Right Lower Leg Assessment:		1.400			0.356		
Foot and Ankle.	Pedal horizontal displacement.			TBA			
	Footwell rupture (-1).			TBA			
	Pedal blocking			TBA			
Foot and Ankle Assessment:		Evaluation based on static measurement (TBA)					
Lower leg, Foot and Ankle Assessment:		1.400			0.356		

EURONCAP

Adult occupant protection

Frontal impact driver

Frontal impact passenger

Front: 15.1

Dummy and restraint analysis

Vehicle equipped with seatbelt pretensioners, driver and passenger head airbag and driver knee airbag.

The driver's knee were protected by the airbag, during the restraint the right femur was loaded up to 6.31 kN, the knee slider was of 10.64 mm.

Structure analysis

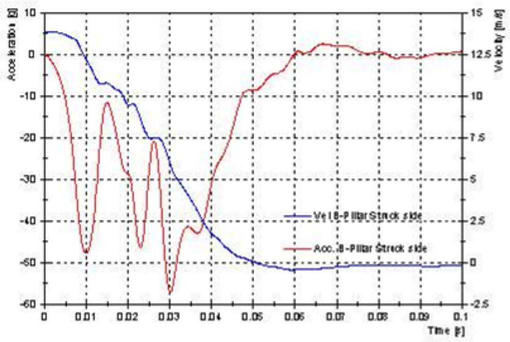
Euro NCAP positions measured in the FWRB test

Location	Before (mm)			After (mm)			Difference (mm)		
	X	Y	Z	X	Y	Z	X	Y	Z
A-Pillar Left Top	472,5	-684,9	602,2	473,1	-686,2	603,3	0,6	-1,4	1,2
A-Pillar Left Bottom	474,4	-687,0	170,9	474,5	-688,7	174,8	0,0	-1,7	3,8
B-Pillar Left Top	1570,3	-659,6	658,6	1570,7	-660,8	658,4	0,4	-1,2	-0,2
B-Pillar Right Top	1572,7	677,1	670,2	1571,8	677,3	669,8	-0,9	0,2	-0,4
B-Pillar Left Bottom	1513,8	-700,6	189,7	1514,4	-701,2	189,5	0,6	-0,6	-0,2
B-Pillar Right Bottom	1520,4	720,5	196,6	1521,2	721,3	195,7	0,9	0,8	-0,9
Steering Wheel	725,1	-327,2	662,8	709,7	-325,0	670,9	-15,4	2,2	8,1
Accelerator pedal	355,2	-159,3	183,8	373,6	-163,0	191,0	18,4	-3,8	7,2
Brake pedal	369,2	-268,6	220,4	385,3	-264,2	220,7	16,1	4,4	0,3
Clutch pedal	366,3	-385,9	222,3	332,3	-384,2	201,1	-34,0	1,6	-21,2

Supermini 2 FWRB Accelerations

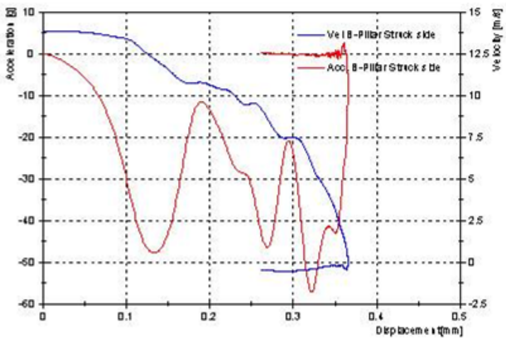
Time

B–Pillar Left side



Displacement

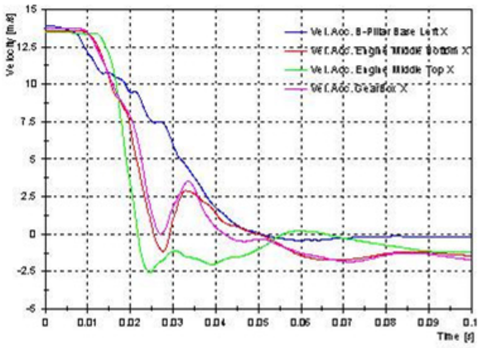
B–Pillar Left side



Supermini 2 FWRB Engine Analysis

Time

B–Pillar Left side

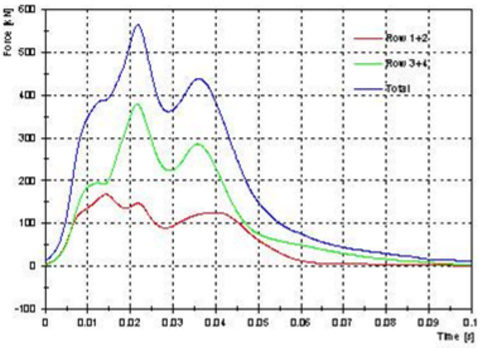


The velocities of engine and gear box drop from 15 to 27 ms. At 27 ms both are stopped due to the contact with the rigid wall.

Supermini 2 FWRB Load Cell Wall

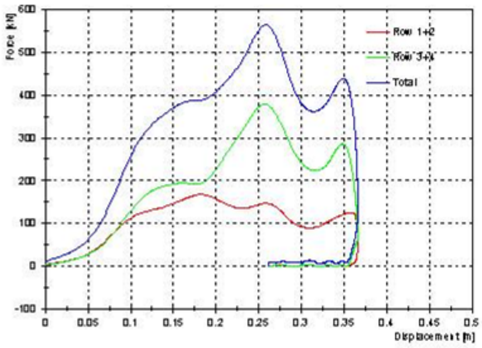
Time

B–Pillar Left side



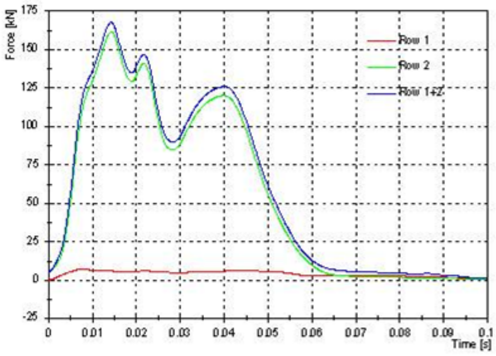
Displacement

B–Pillar Left side



Total: 202 kN @ 6.9ms Row 1+2: 94 kN @ 6.9ms Row 3+4: 98 kN @ 6.9ms

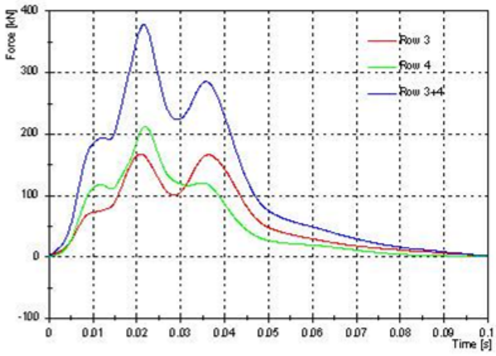
Supermini 2 FWRB Load Cell Wall



Row 1+2: 94 kN @ 6.9ms

Row 1: 7 kN @ 6.9ms

Row 2: 87 kN @ 6.9ms



Row 3+4: 98 kN @ 6.9ms

Row 3: 44 kN @ 6.9ms

Row 4: 54 kN @ 6.9ms

FWRB Metric

- Current status

Metric @ total LCW force 200 kN

F3+F4>80 kN	F3+F4=98 kN	PASS
0.2<(F4/(F4+F3)<0.8	F4/(F4+F3)=0.55	PASS

- Metric upgrade

Metric @ total LCW force 200 kN

F3+F4>(100 kN-LR)	LR=35; F3+F4=98 kN	PASS
F4>35 kN	F4=54 kN	PASS
F3>(35 kN-LR)	F3=44 kN	PASS

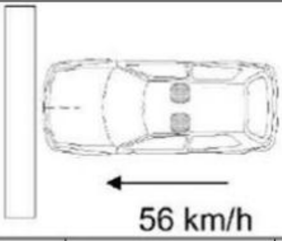
Limit Reduction = Min [(F2+F1-25 kN); 35 kN]

Conclusions

- Dummy injury bellow R94 limits, however, high loading in femurs and lower legs were observed
- LCW recorded 200 kN at 6.9 ms, before engine dumps, which starts at 15 ms
- Current status and Metric Upgrade of FWRB PASS

CITYCAR 1 FWDB 56 KM/H @ RENAULT

Test Date	21/12/11
Location	UTAC
Topic	Full Width test
Mass Ratio	N/A
Test Number	AFFSEP1102 988
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:	Super-mini	Barrier:	Full Width
Brand/type	City Car 1		150 mm 0.34 MPa
Impact side:	Front		150 mm 1.71 MPa
Speed:	56 km/h		Segmented
Overlap:	100%	Impact accuracy	5 mm left 5 mm up
Test mass:	1174 kg	LCW ground clearance	80 mm
Dummy:	LHS - Hybrid III 50th RHS - Hybrid III 5th	LCW / barrier dimensions	2m wide 1m high

Test objectives: Test performed with FIMCAR WP3 configurations in order to check City Car 1 with WP3 criteria.

Test parameters

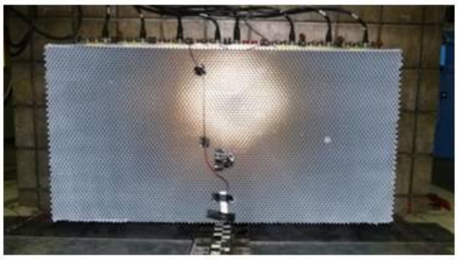
- **Vehicle data: City Car 1**
- **Engine / Transmission: Petrol / Manual gearbox**
- **Test speed: 56kph**
- **Test weight: F 675 kg / R 499 kg Total 1174 kg**
- **Test impact accuracy: lateral and vertical**
- **Test vehicle status:**
  - **Test mass as Euro NCAP test**

Pre-test Pictures
Vehicle




Pre-test Pictures
Barrier

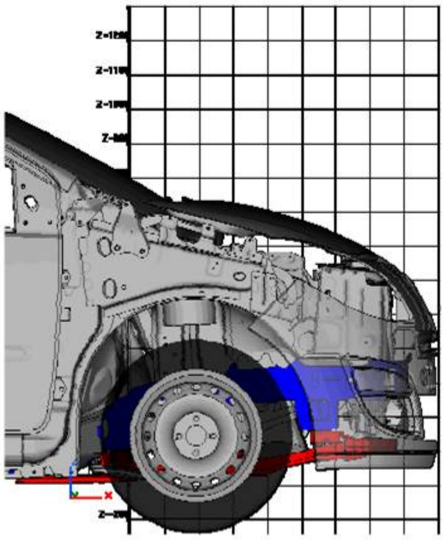




Description of front-end structure

Pictures / description of front-end structure:

City Car 1 front end structure composed of two load path (crossbeam and advanced subframe), with vertical connections between both.



SEVENTH FRAMEWORK PROGRAMME

Description of front-end structure

City car 1 front end structure is composed of two load paths (crossbeam and advanced subframe), with 2 vertical connections between both.

The advanced subframe is stiffer than the crossbeam

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Vehicle

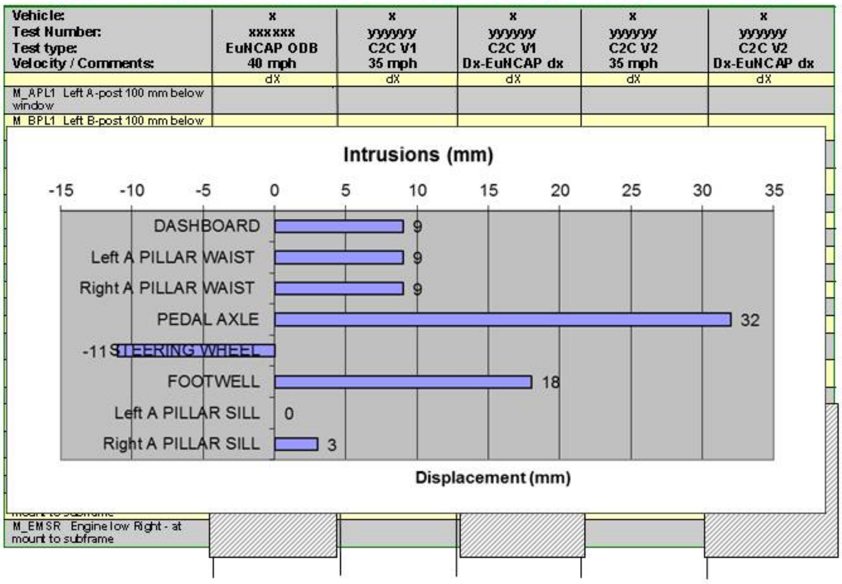



Post-test Pictures
Barrier



Additional pictures to show detailed deformation of car or barrier

Example: Static deformations in x-direction, y and z also collected.



First 13 rows are EuNCAP positions, Brake Pedal Axle defined by UTAC for PDB tests, last 6 rows are for structural interaction analysis.

Structural results

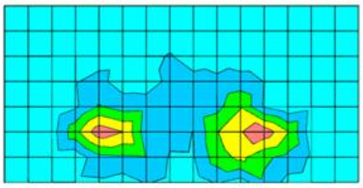
- Vehicle 1

Good general comportement of the occupant space.

Barrier

Deformation permits to well see the position of cross beam and subframe.

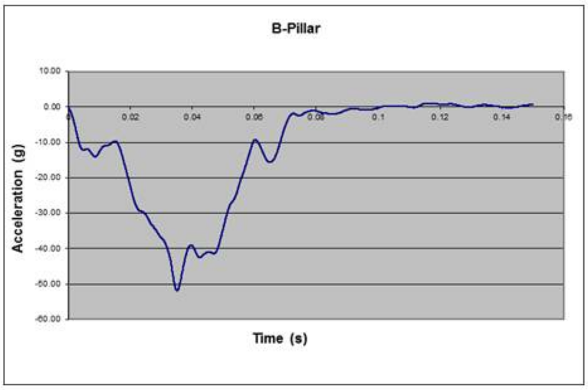
Deformation from subframe are at least as important thant those from crossbeam

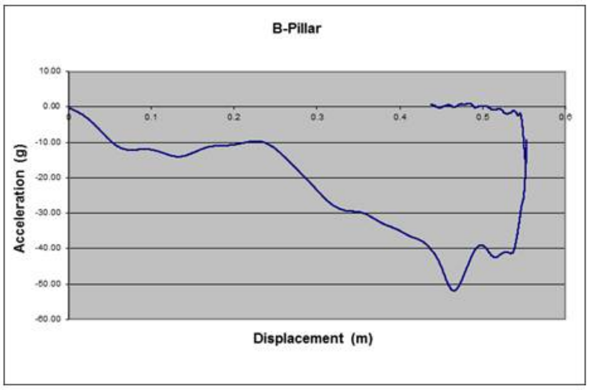


Car Accelerations vs.

Time

Displacement

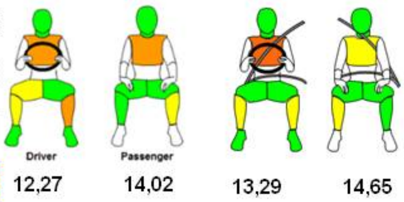




Dummy criteria comparison

FWDB (without modifiers)

EuroNCAP frontal assessment	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	64.40	4.000	70.80	4.000
HIC36	598		855.00	
Resultant Acc. 3 msec exceedence - g	63.30		63.30	
Unstable airbag contact, Bottoming out (-1)		0.000		0.000
Steering wheel displacement (-1) mm	0	0.000		
Incorrect airbag deployment		0.000		0.000
NECK				
Shear level exceeded - kN	0.38	4.000	0.84	4.000
duration of exceedence - ms	0		0.00	
Tension level exceeded - kN	1.97	4.000	1.35	4.000
duration of exceedence - ms	0		0.00	
Extension - Nm	7.41	4.000	19.74	4.000
CHEST				
Compression - mm	35.10	2.129	34.30	2.757
Viscous criterion - m/s	0.27	4.000	0.32	4.000
Steering wheel contact (-1)		0.000		
A-Pillar displacement (-2) mm	0	0.000		
Unstable passenger compartment (-1)		0.000		
Shoulder belt load - kN	4.43		4.55	
Chest Incorrect Airbag Deployment Modifier		0.000		0.000
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0.0	4.000	0.2	4.000
Left Femur Compression level exceeded - kN	2.24	4.000	1.8	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
Incorrect airbag deployment		0.000		0.000
Right Knee Slide - mm	9.9	4.000	0.2	4.000
Right Femur Compression level exceeded - kN	4.28	3.851	2.9	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
Incorrect airbag deployment		0.000		0.000
LOWER LEG				
Left compression - kN	2.55	3.893	0.79	4.000
Left Upper Tibia Index	0.45	3.773	0.49	3.387
Left Lower Tibia Index	0.74	2.439	0.40	4.000
pedal vertical (-1) mm	0	0.000		
Right compression - kN	3.03	3.273	1.35	4.000
Right Upper Tibia Index	0.81	3.087	0.39	4.000
Right Lower Tibia Index	0.33	4.000	0.22	4.000
pedal vertical (-1) mm	0	0.000		
FOOT and ANKLE				
pedal horizontal displacement - mm	0	4.000		
Footwell Rupture (-1)		0.000		
Pedal Blocking (-1)	0	0.000		
SUMMARY				
Head and Neck assessment		4.000		4.000
Chest assessment		2.129		2.757
Knee, Femur and Pelvis assessment		3.851		4.000
Lower Leg, Foot and Ankle Assessment		2.439		3.387



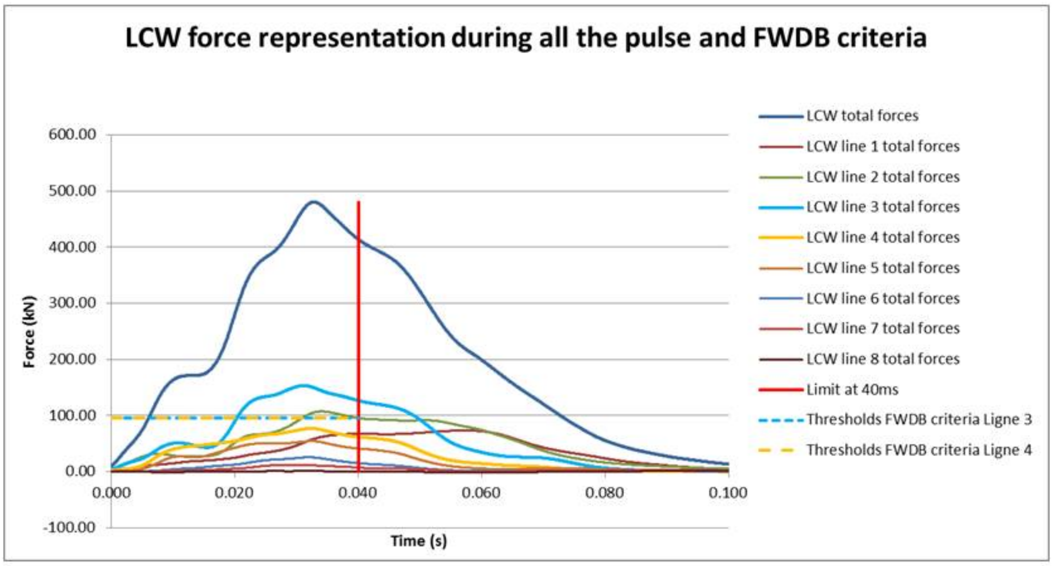
EURONCAP (without modifiers)

EuroNCAP frontal assessment	Driver	Points	Passenger	Points
HEAD				
Peak resultant acceleration - g	53.20	4.000	45.51	4.000
HIC36	551		313.22	
Resultant Acc. 3 msec exceedence - g	57.50		49.33	
Unstable airbag contact, Bottoming out (-1)		0.000		
Steering wheel displacement (-1) mm	12	0.000		0.000
NECK				
Shear level exceeded - kN	0.50	4.000	0.87	4.000
duration of exceedence - ms	0		0.00	
Tension level exceeded - kN	1.93	4.000	1.13	4.000
duration of exceedence - ms	0		0.00	
Extension - Nm	38.60	4.000	3.30	4.000
CHEST				
Compression - mm	33.50	2.380	29.00	3.000
Viscous criterion - m/s	0.75	4.000	0.09	4.000
Steering wheel contact (-1)		0.000		
A-Pillar displacement (-2) mm	-31	0.000		
Unstable passenger compartment (-1)		0.000		
Shoulder belt load - kN	5.00		4.32	
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0.4	4.000	0.2	4.000
Left Femur Compression level exceeded - kN	0.91	4.000	1.7	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
Right Knee Slide - mm	1.0	4.000	0.9	4.000
Right Femur Compression level exceeded - kN	2.53	4.000	0.2	4.000
duration of exceedence - ms	0		0.0	
Variable contact (-1)		0.000		0.000
Concentrated loading (-1)		0.000		0.000
LOWER LEG				
Left compression - kN	1.35	4.000	0.29	4.000
Left Upper Tibia Index	0.35	4.000	0.21	4.000
Left Lower Tibia Index	0.84	2.930	0.18	4.000
Brake pedal vertical (-1) mm	-43	0.000		
Right compression - kN	2.78	3.300	2.18	3.300
Right Upper Tibia Index	0.43	3.850	0.43	3.850
Right Lower Tibia Index	0.30	4.000	0.30	4.000
Brake pedal vertical (-1) mm	-43	0.000		
FOOT and ANKLE				
Brake pedal horizontal displacement - mm	75	4.000		
Footwell Rupture (-1)		0.000		
Pedal Blocking (-1)	47	0.000		
SUMMARY				
Head and Neck assessment		4.000		4.000
Chest assessment		2.380		3.000
Knee, Femur and Pelvis assessment		4.000		4.000
Lower Leg, Foot and Ankle Assessment		2.930		3.850

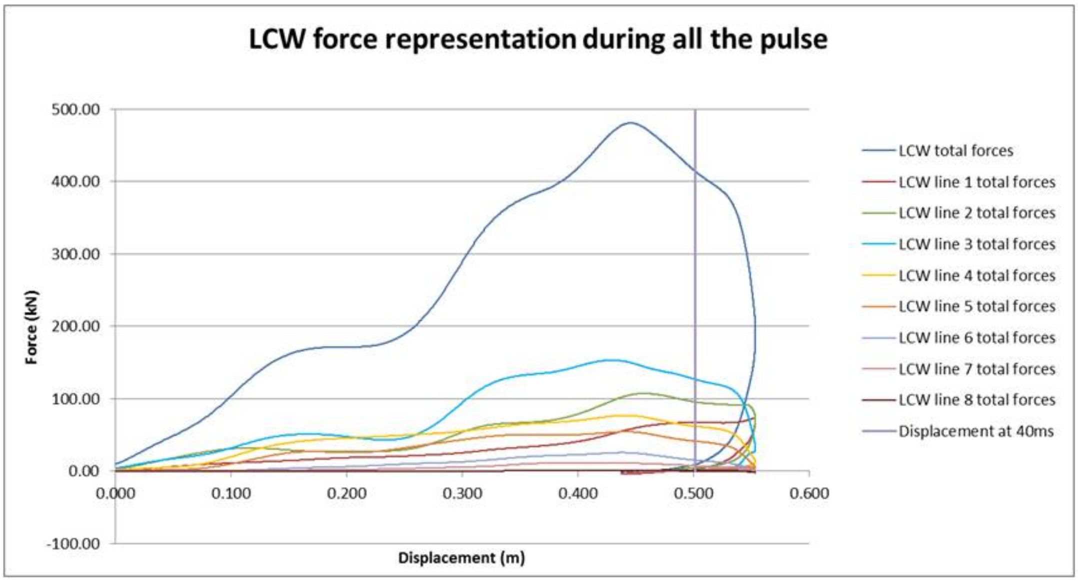
Dummy and restraint analysis

- Restraint fire time,
  - Seat belt at 10ms for both front passenger,
  - Airbag at 16ms for both front passenger

LCW force vs time



LCW force vs B-pillar displacement



Metrics evaluation

Method B(1) FWDB: up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	City car 1 FWDB	
	Value	OK/KO
Time at 400kN (ms)	27.1	NA
F3+F4 > 180 kN (kN)	206.72	OK
F3 > 85 kN (kN)	138.93	OK
F4 > 85 kN (kN)	67.79	KO
Global	KO	

Method B(1) FWDB: up to 40 ms → F3 > 75 kN AND F4 > 75 kN

	City car 1 FWDB	
	Value	OK/KO
Up to 40 ms, F3 > 75 kN (kN)	126.55	OK
Up to 40 ms, F4 > 75 kN (kN)	61.67	KO
Global	KO	

Upgrade1 FWDB: up to 40 ms → F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)]

	City car 1 FWDB		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	153.01	96.15	OK
F4 > MIN[100, 0.2Ft40]	76.79	96.15	KO
Global	KO		

fontal impact and compatibility assessment research

SEVENTH FRAMEWORK PROGRAMME

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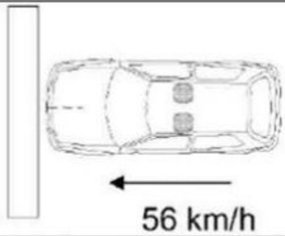
Conclusions

- City car 1 has higher dummy valuse compared to the Euro NCAP test
- The vehicle has its PEAS beneath the common alignment zone.
- LCW forces in row 4 are low, thus it does not fulfill the metric

MINICAR 2 FWDB 56 KM/H @ FIAT

Test Date	26/09/2011
Location	FIAT Safety Center
Topic	Full Width test
Mass Ratio	N/A
Test Number	17423
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:	Super-mini	Barrier:	Full Width 150 mm 0.34 MPa 150 mm 1.71 MPa Segmented
Brand/type	Supermini 2	Impact accuracy	5 mm left 4 mm up
Impact side:	Front	LCW ground clearance	80 mm
Speed:	56.49 km/h	LCW / barrier dimensions	2000 mm wide 750 mm high
Overlap:	100 %		
Test mass:	1106 kg		
Dummy:	LHS – Hybrid III 50th RHS – Hybrid III 5th		

Test objectives:

Test parameters

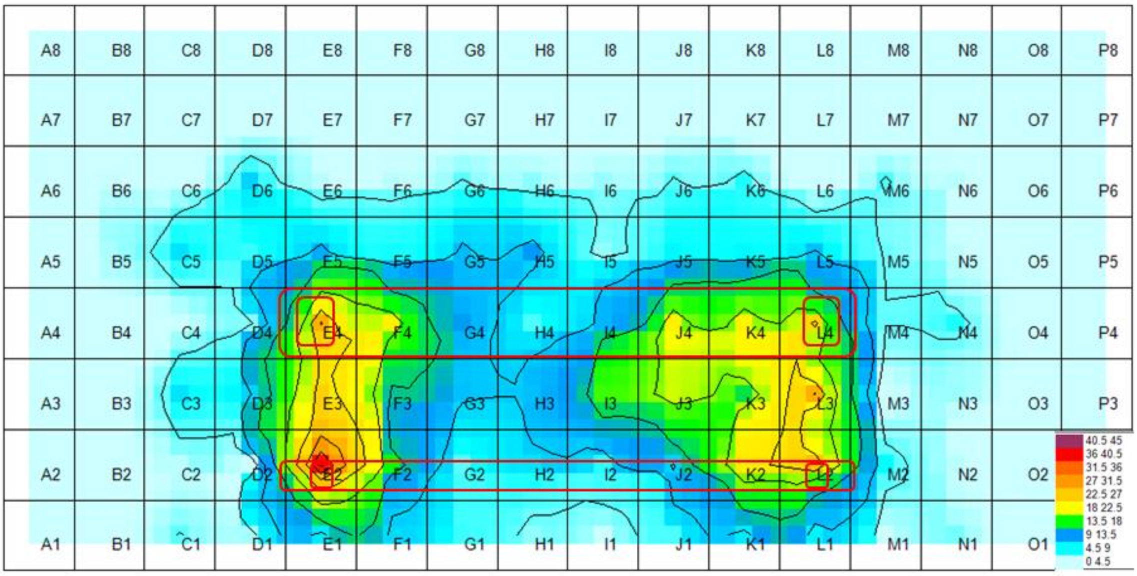
- Vehicle data: Supermini 2 LHD
- Engine / Transmission: 1.2 Petrol / Manual
- Test speed: 56.49
- Test weight: F 666 kg / R 440 kg Total 1106 kg
- Test impact accuracy: 5 mm left, 4 mm up
- Test vehicle status:
  - Standard ride heights:
  - Fender height R F 628
    Fender height L F 627
    Fender height R R 636
    Fender height L R 634

Pre-test Pictures
Vehicle 1

Pre-test Pictures
Barrier



Alignment of Vehicle Structure with LCW



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Post-test Pictures
Vehicle 1

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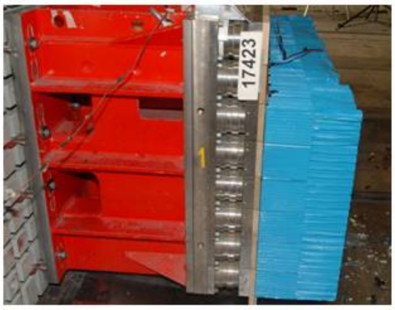
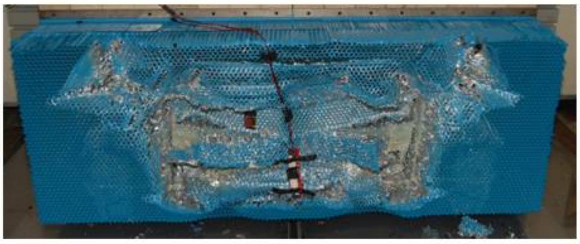
Post-test Pictures
Barrier





Additional pictures (1/2)

Additional pictures (2/2)

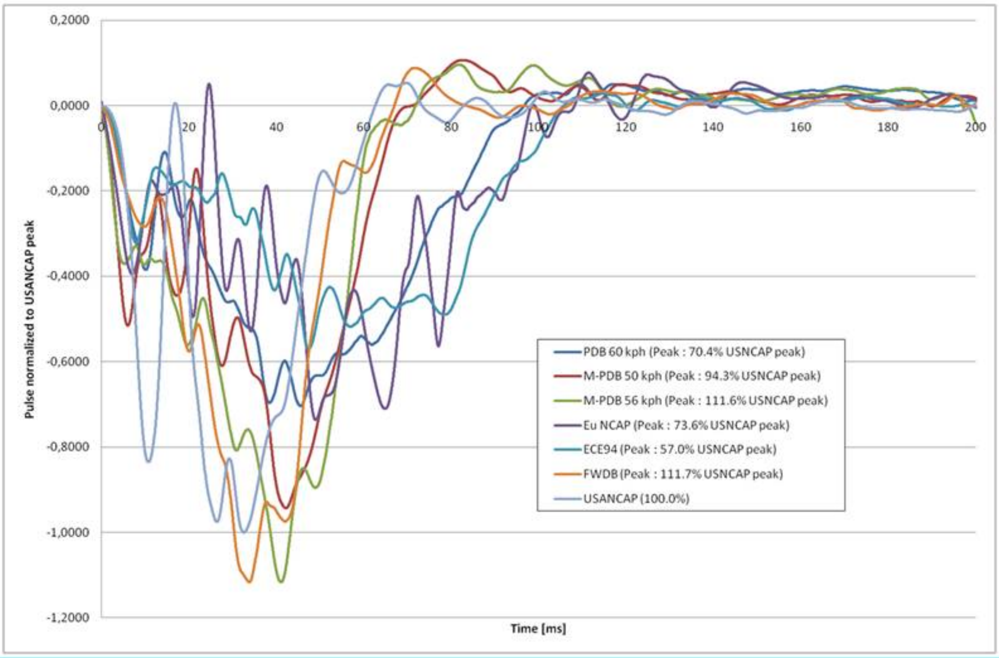
Structural results

- Supermini 2: main rails and third load paths folded, good stability of passenger compartment and door rings.

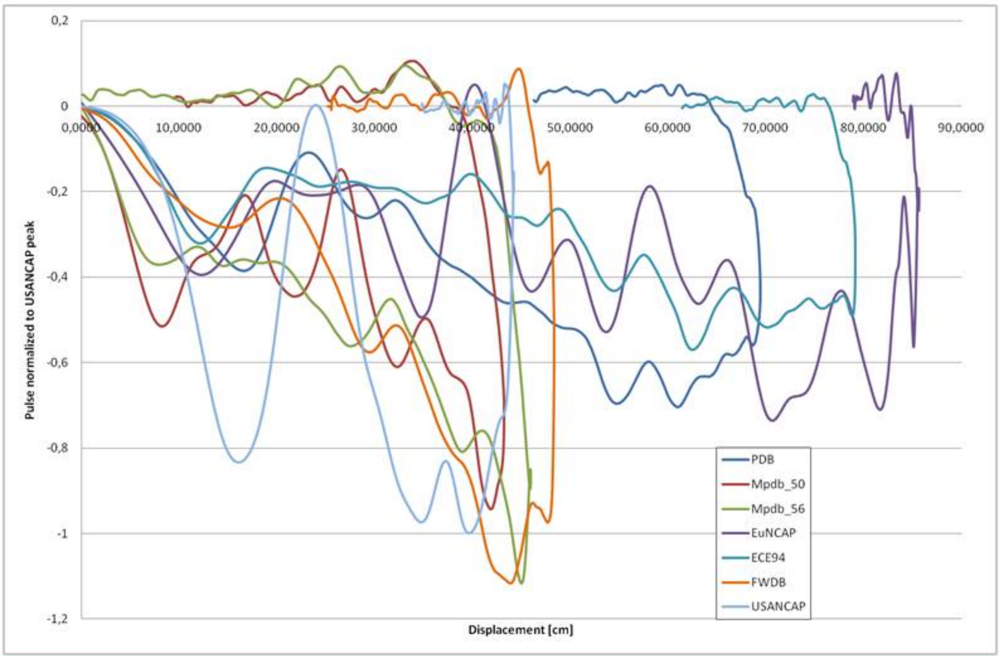
Static measurements

Frontal Impact	Rearw. Steering wheel displacment	Upward Steering wheel displacement	Lateral Steering wheel displacement	Rearw. A pillar displacement	Rearward pedal fixation displacement
Remarks	(mm)	(mm)	(mm)	(mm)	(mm)
FWDB - 56kph - 17423	-23	8	4	1.7	22
	Occupant compartment stability	Footwell Ruptures	Rearw. Pedals displacement	Upward. Pedals displacement	G max SAE 60
			(mm)	(mm)	(g)
FWDB - 56kph - 17423	Yes	No	5 (accel)	0 (clutch)	62

Normalized acceleration Vs. time



Normalized acceleration Vs. displacement



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Dummy criteria comparison

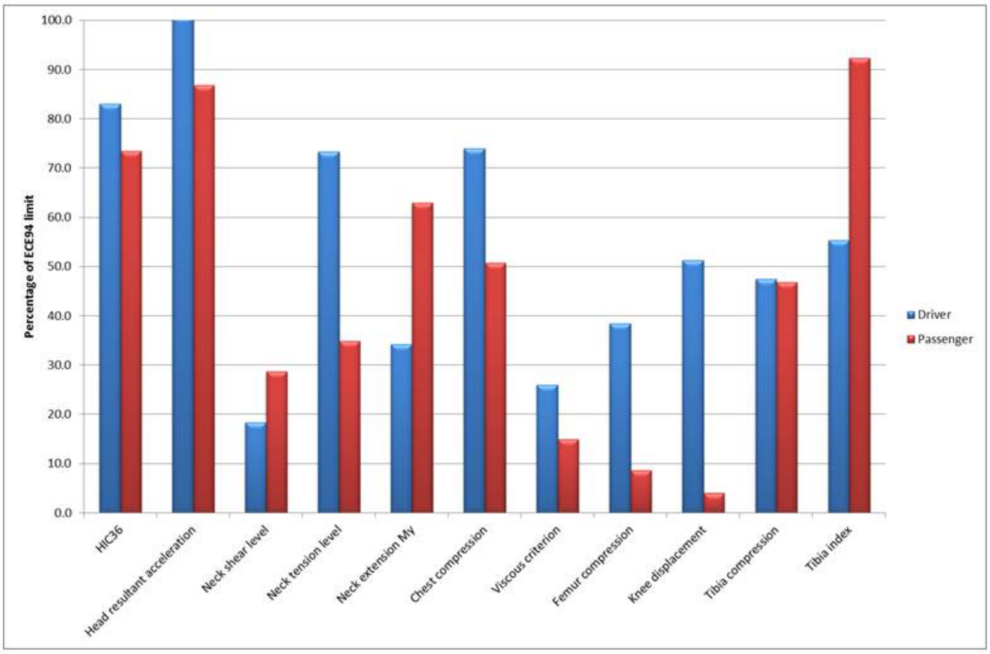
FWDB

	Driver		Passenger	
HEAD	Value	Points Scored	Value	Points Scored
Peak resultant acceleration - g	80.74	1.934	69.42	4.000
HIC_{36}	830.78		734.90	4.000
Resultant Acc. 3 msec exeedence - g	78.74		68.43	4.000
Head Assessment		1.934		4.000
NECK				
Shear level exceeded - kN	0.57	4.000	0.89	4.000
Tension level exceeded - kN	2.42	4.000	1.15	4.000
Extension - Nm	19.53	4.000	35.85	4.000
Neck Assessment		4.000		4.000
Head and Neck Assessment		1.934		4.000
CHEST				
Compression - mm	37.00	1.857	25.40	3.514
Viscous criterion - m/s	0.26	4.000	0.15	4.000
Shoulder belt load - kN	3.59		3.71	
Chest Assessment		1.857		3.514
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	1.4	4.000	0.4	4.000
Left Femur Compression level exceeded - kN	0.48	4.000	0.53	4.000
duration of exceedence - ms	0		0	
Left Knee, Femur and Pelvis Assessment		4.000		4.000
Right Knee Slide - mm	7.7	3.262	0.6	4.000
Right Femur Compression level exceeded - kN	3.84	3.970	0.86	4.000
duration of exceedence - ms	0		0	
Right Knee, Femur and Pelvis Assessment		3.262		4.000
Knee, Femur and Pelvis assessment		3.262		4.000
LOWER LEG				
Left compression - kN	3.43	3.047	3.75	2.833
Left Upper Tibia Index	0.58	3.200	0.48	3.644
Left Lower Tibia Index	0.41	3.956	0.61	3.067
Left Lower Leg assessment		3.047		2.833
Right compression - kN	3.80	2.800	3.22	3.187
Right Upper Tibia Index	0.72	2.578	1.20	0.444
Right Lower Tibia Index	0.61	3.067	0.99	1.378
Right Lower Leg assessment		2.578		0.444
Lower Leg, Foot and Ankle assessment		2.578		0.444
SUMMARY				
Head and Neck assessment		1.934		4.000
Chest assessment		1.857		3.514
Knee, Femur and Pelvis assessment		3.262		4.000
Lower Leg, Foot and Ankle Assessment		2.578		0.444
TOTAL DRIVER FRONTAL		9.631		11.958

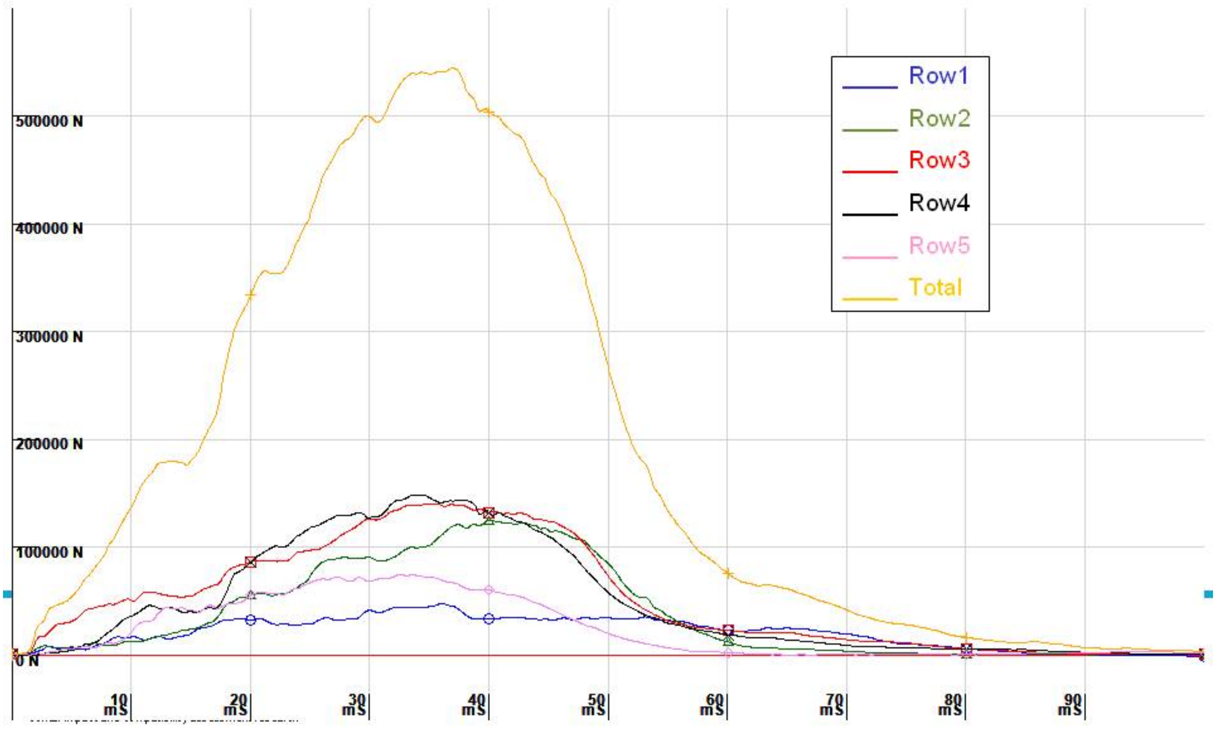
EU-NCAP

	Driver		Passenger	
HEAD	Value	Points Scored	Value	Points Scored
Peak resultant acceleration - g	58.98	4.000	45.56	4.000
HIC_{36}	562.75	4.000	356.68	4.000
Resultant Acc. 3 msec exeedence - g	58.71	4.000	44.63	4.000
Head Assessment		4.000		4.000
NECK				
Shear level exceeded - kN	0.67	4.000	0.28	4.000
Tension level exceeded - kN	1.72	4.000	0.67	4.000
Extension - Nm	18.85	4.000	18.38	4.000
Neck Assessment		4.000		4.000
Head and Neck Assessment		4.000		4.000
CHEST				
Compression - mm	23.27	3.820	22.43	3.940
Viscous criterion - m/s	0.08	4.000	0.10	4.000
Shoulder belt load - kN	3.77		3.24	
Chest Assessment		3.820		3.940
KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	0.6	4.000	0.5	4.000
Left Femur Compression level exceeded - kN	0.52	4.000	0.28	4.000
Variable contact		0.000		0.000
Left Knee, Femur and Pelvis Assessment		4.000		4.000
Right Knee Slide - mm	2.6	4.000	0.3	4.000
Right Femur Compression level exceeded - kN	0.59	4.000	0.30	4.000
Variable contact		0.000		0.000
Right Knee, Femur and Pelvis Assessment		4.000		4.000
Knee, Femur and Pelvis assessment		4.000		4.000
LOWER LEG				
Left compression - kN	3.07	3.290	2.24	3.840
Left Upper Tibia Index	0.47	3.690	0.35	4.000
Left Lower Tibia Index	0.52	3.470	0.22	4.000
Left Lower Leg assessment		3.290		3.840
Right compression - kN	2.36	3.760	1.27	4.000
Right Upper Tibia Index	0.43	3.870	0.35	4.000
Right Lower Tibia Index	0.39	4.000	0.42	3.910
Right Lower Leg assessment		3.760		3.910
Lower Leg, Foot and Ankle assessment		3.290		3.840
SUMMARY				
Head and Neck assessment		4.000		4.00
Chest assessment		3.820		3.94
Knee, Femur and Pelvis assessment		4.000		4.00
Lower Leg, Foot and Ankle Assessment		3.290		3.84
TOTAL FRONTAL		15.110		15.780

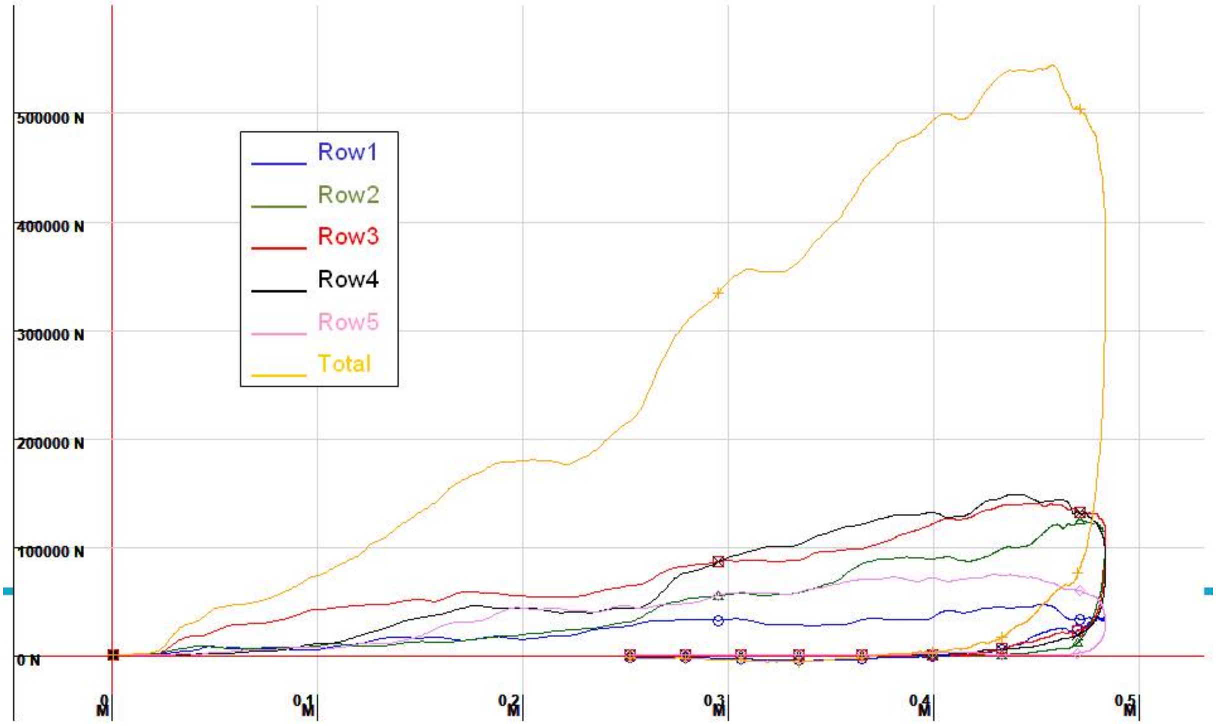
Dummy Criteria Comparison - % of Reference Value (Reg 94)



LCW force vs time



LCW force vs B-pillar displacement



Metrics evaluation

Method B(1) FWDB: up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	Supermini 2 FWDB	
	Value	OK/KO
Time at 400kN (ms)	24.7	NA
F3+F4 > 180 kN (kN)	211.7	OK
F3 > 85 kN (kN)	96.1	OK
F4 > 85 kN (kN)	115.5	OK
Global	OK	

Method B(2) FWDB: up to 40 ms → F3 > 75 kN AND F4 > 75 kN

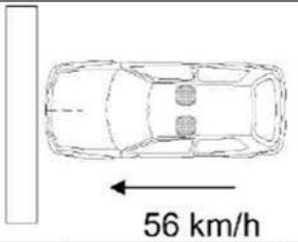
	Supermini 2 FWDB	
	Value	OK/KO
Up to 40 ms, F3 > 75 kN (kN)	140.1	OK
Up to 40 ms, F4 > 75 kN (kN)	148.1	OK
Global	OK	

Upgrade1 FWDB: up to 40 ms → F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)]

	Supermini 2 FWDB		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	140.1	108.7	OK
F4 > MIN[100, 0.2Ft40]	148.1	108.7	OK
Global	OK		

SUV 1 FWDB 56 KM/H @ TRL

Test Date	23/03/12
Location	TRL
Topic	Full Width test
Mass Ratio	N/A
Test Number	B4767
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:		Barrier:	Full Width
Brand/type	SUV 1		150 mm 0.34 MPa
Impact side:	Front		150 mm 1.71 MPa
Speed:	56 km/h		Segmented
Overlap:	100 %	Impact accuracy	Lost in test
Test mass:	1961kg		
Dummy:	LHS – Hybrid III 50th RHS – Hybrid III 5th both with RibEye chest deflection	LCW ground clearance	80 mm
		LCW barrier dimensions	2m wide 1m high

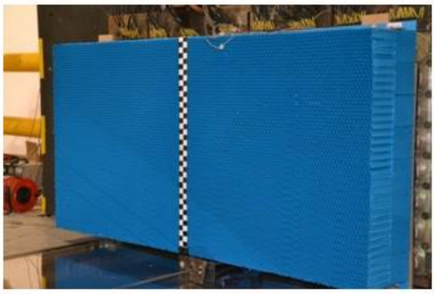
Test parameters

- **Vehicle data: SUV 1**
- **Engine / Transmission: 2.0L DCi / Manual 4WD**
- **Test speed: 55.8km/h**
- **Test weight: F 1147kg / R 814 kg Total 1961 kg**
- **Test impact accuracy: Lost in test**
- **Test vehicle status:**
- - **Standard ride height**
- - **FL = 760mm FR = 758mm**
  - **RL = 757mm RR = 755mm**

Pre-test Pictures
SUV 1



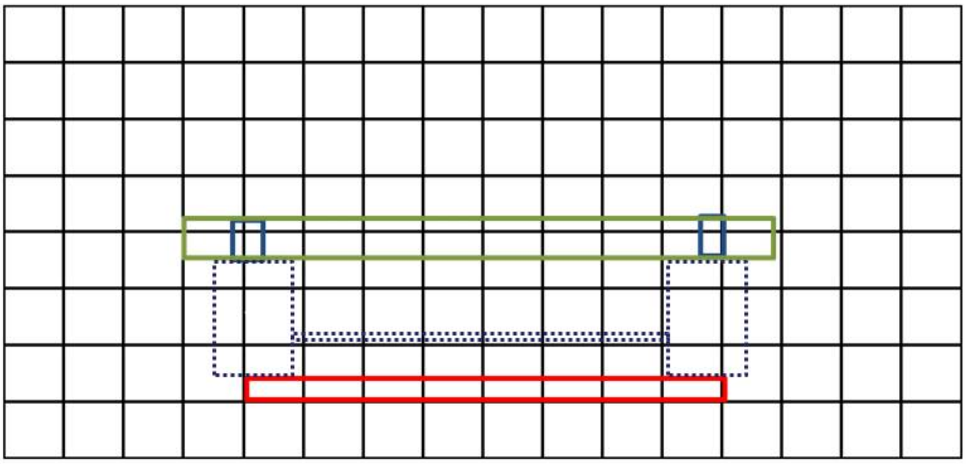

Pre-test Pictures
Barrier

Description of front-end structure

Two main longitudinal rails, each with cross-sectional area (y)59mm x (z)94mm. Bumper crossbeam connecting the two rails horizontally. A hanger from each side of the rails connects to a subframe 26mm rearwards and 209mm below the rails.

Alignment of Vehicle Structure with LCW



Post-test Pictures
Vehicle 1

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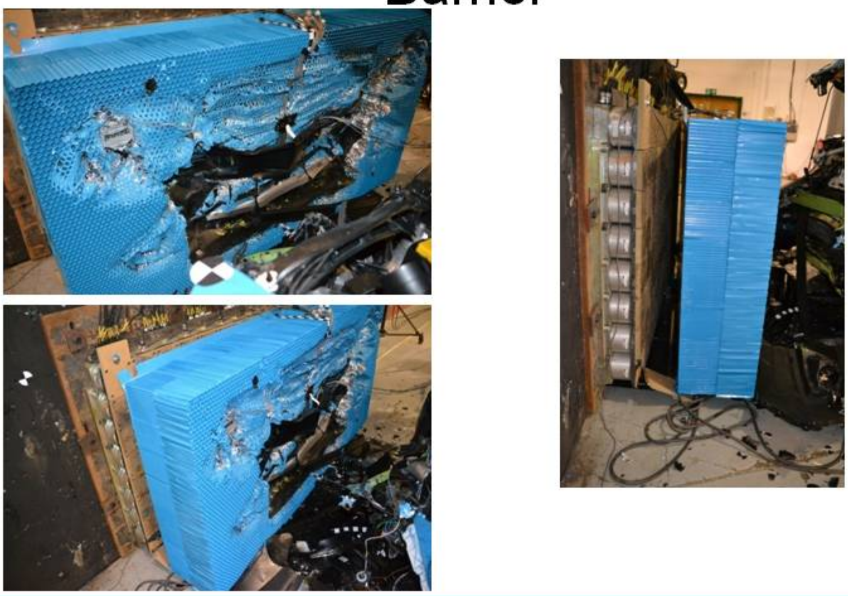
SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Barrier



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Deformation measurements

SUV 1

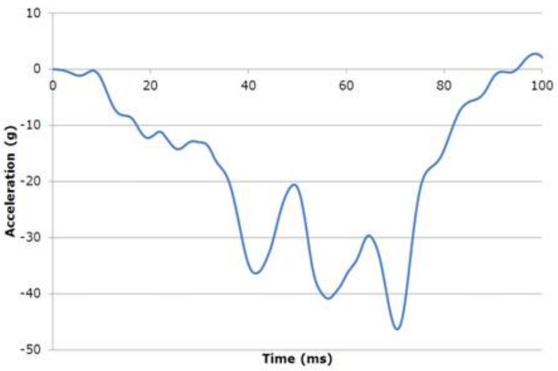
Vehicle:	Renault Koleos
Test Number:	B4767
Test type:	FWDB
Velocity / Comments:	56km/h
	dX (mm)
M_APL1 Left A-post 100 mm below window	-2
M_BPL1 Left B-post 100 mm below window	-1
M_APL3 Left A-post 100 mm above sill	0
M_BPL3 Left B-post 100 mm above sill	0
M_SCT Top of steering column	38
M_AP Accelerator pedal	-12
M_AP2 Accelerator pedal 200N	18
M_BP Brake pedal	56
M_BP2 Brake pedal 200 N	148
M_CP Clutch pedal	106
M_CPA Brake Pedal Axle (hinge)	-
M_CP2 Clutch pedal 200 N	110
M_BPR1 Right B-post 100 mm below window	-1
M_APR3 Right B-post 100 mm above sill	-2
M_FSML Left front end of side member	-
M_FSMR Right front end of side member	-
M_SFL Subframe left front side	-
M_SFR Subframe right front side	-
M_EMSL Engine low Left - at mount to subframe	-
M_EMSR Engine low Right - at mount to subframe	-

Structural results

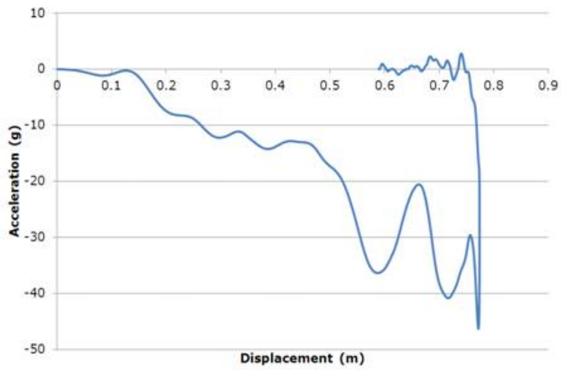
- Vehicle
  - Crumpling and bending of main rails with much greater deformation of RHS rail compared to LHS rail.
  - Bending of bumper crossbeam in middle
- Barrier
  - Barrier deformation as expected for large vehicle with significant deformation in areas of vehicle with structure
  - Barrier bottomed out in locations of longitudinal rails

Car Accelerations vs.

Time

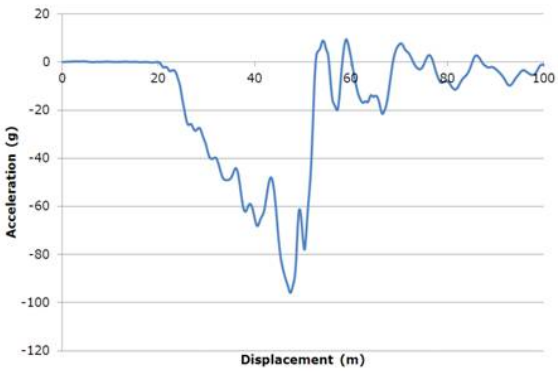


Displacement

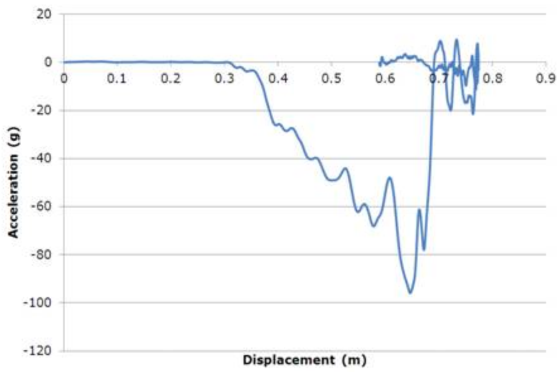


Engine acceleration vs.

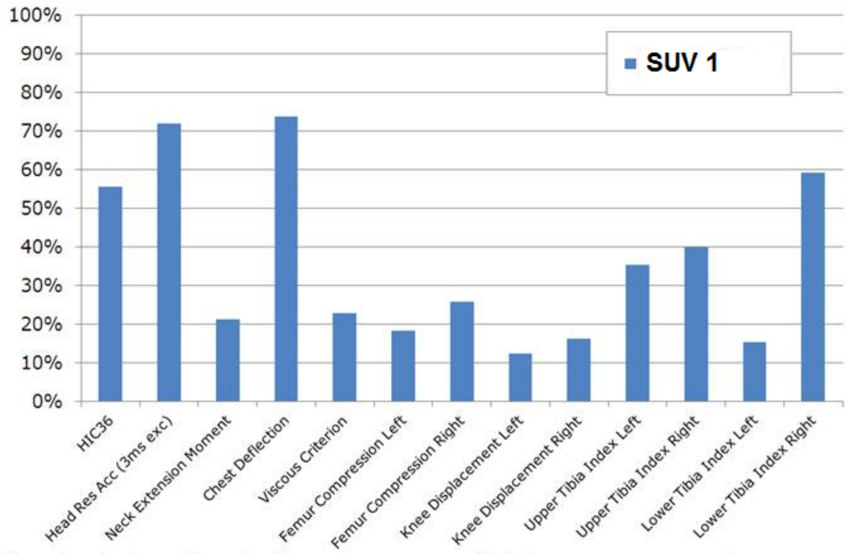
Time



Vehicle displacement



Driver Dummy Criteria Comparison - % of Reg 94 limits

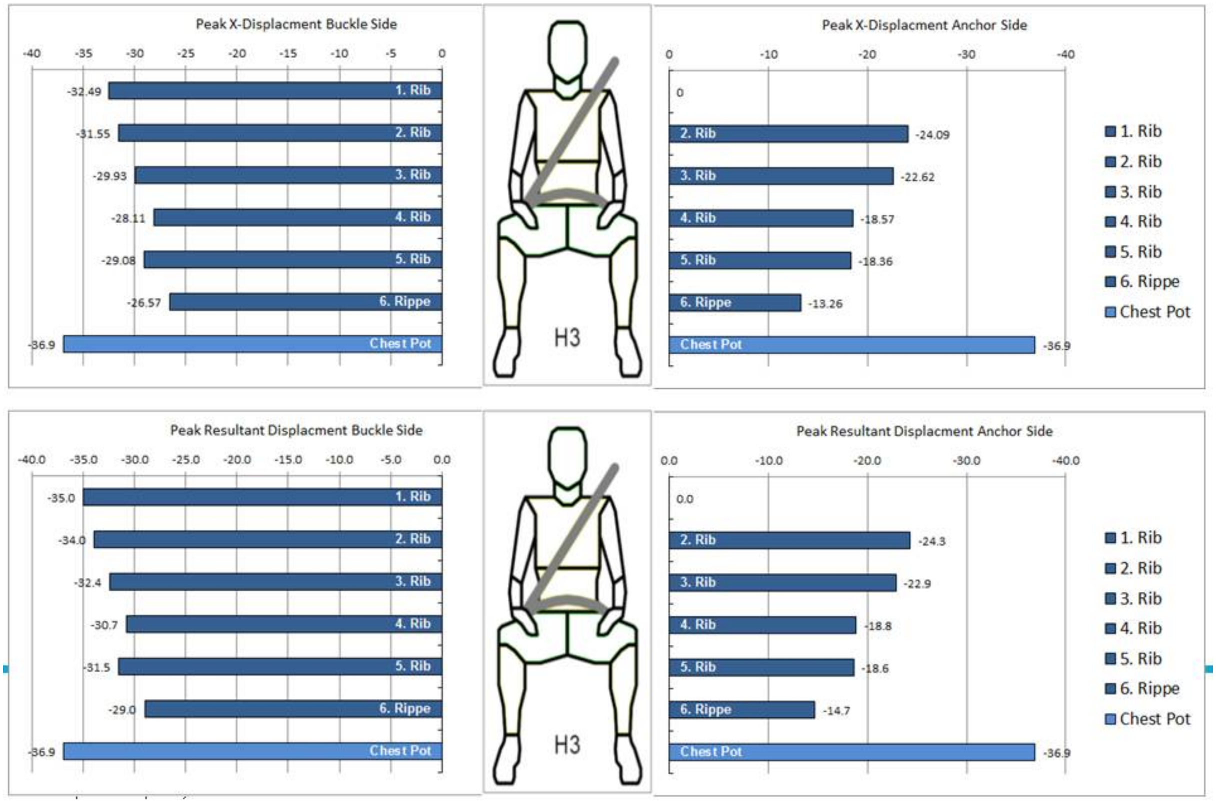


Note: After test shoulder belt anchorage point for passenger dummy could move ~ 2 cm up/down in a manner which indicated that height adjustment mechanism was broken

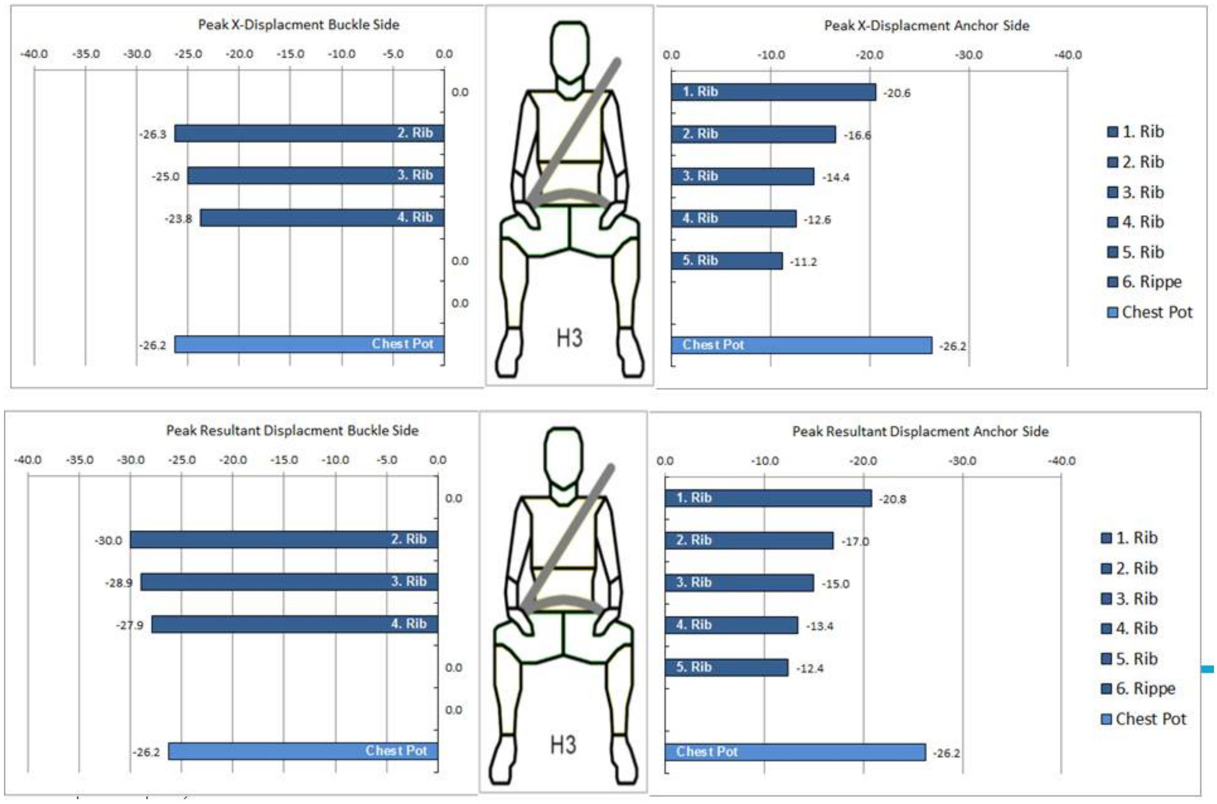
Dummy and restraint analysis – airbag firing times

Driver	Passenger
17ms	17ms

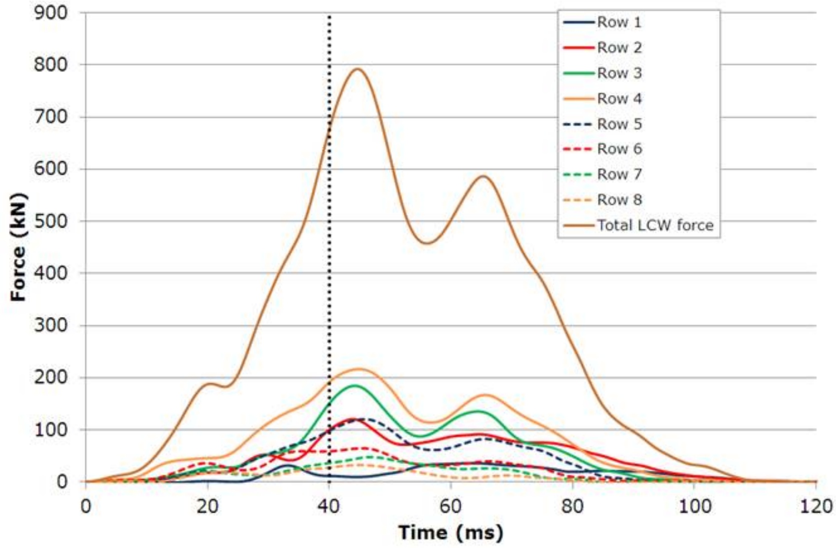
RibEye analysis - driver



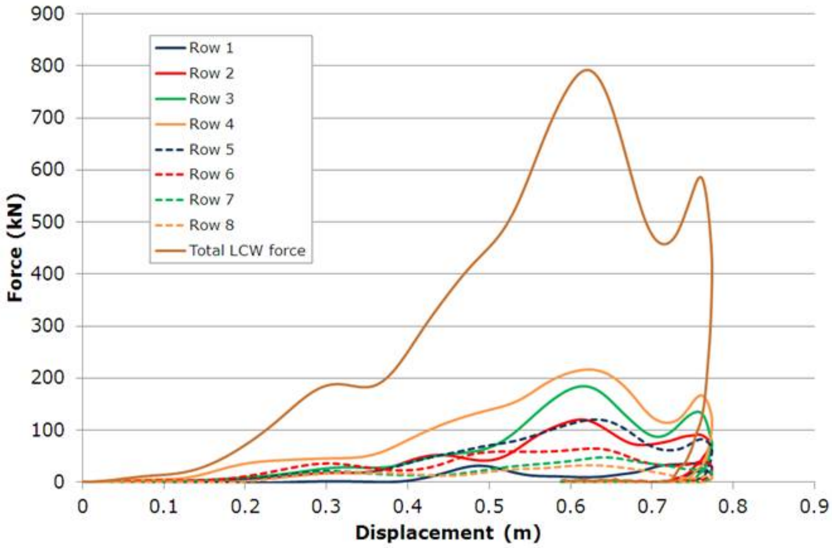
RibEye analysis – front seat passenger



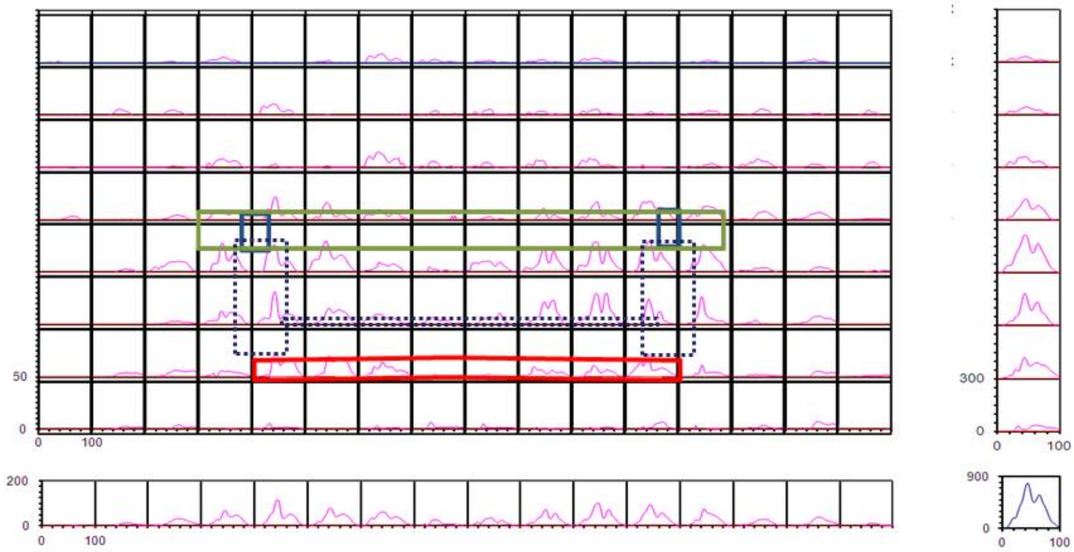
LCW force vs time



LCW force vs B-pillar displacement



LCW cell forces



Metrics evaluation

Method B(1) FWDB: up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN

	SUV 1 FWDB	
	Value	OK/KO
Time at 400kN (ms)	31.8	NA
F3+F4 > 180 kN (kN)	182.6	OK
F3 > 85 kN (kN)	56.8	NO
F4 > 85 kN (kN)	125.8	OK
Global	OK	

Method B(1) FWDB: up to 40 ms → F3 > 75 kN AND F4 > 75 kN

	SUV 1 FWDB	
	Value	OK/KO
Up to 40 ms, F3 > 75 kN (kN)	151	OK
Up to 40 ms, F4 > 75 kN (kN)	192	OK
Global	OK	

Upgrade1 FWDB: up to 40 ms → F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)]

	SUV 1 FWDB		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	151	135.4	OK
F4 > MIN[100, 0.2Ft40]	192	135.4	OK
Global	OK		

Conclusions

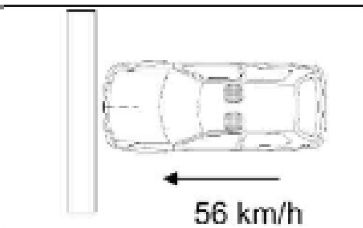
- LCW
  - Likely that hanger structure between rails and subframe contributed significantly to load on row 3 because of its large frontal area
- LCW metrics
  - SUV 1 met:
    - Up to 40 ms F3 > [MIN(100, 0.2Ft40)] AND F4 > [MIN(100, 0.2Ft40)
    - Up to 40 ms → F3 > 75 kN AND F4 > 75 kN
  - SUV 1 did not meet:
    - Up to 400 kN → F3 + F4 > 180 kN AND F3 > 85 kN AND F4 > 85 kN
- Dummy results
  - All driver dummy values less than 73% of current R94 performance limits

SUV 2 FWDB 56 KM/H @ IDIADA

WP3 testing activities
SUV 2
FWDB at IDIADA

SUV 2 FWDB test

Test Date	Aug. 31, 2012
Location	IDIADA
Topic	FWDB
Mass Ratio	NA
Test Number	123514FF
Test Protocol	FIMCAR



Vehicle 1:	4x4	Ride height measured at wheel arch:
Brand/type	SUV 2	
Impact side:	Front	
Speed:	56 km/h	Front left: 742 mm
Overlap:	100 %	Front right: 748 mm
Test mass:	1846.0 kg	
Dummy:	LHS – HIII 50%	Rear left: 750 mm
	RHS – HIII 5% Female	Rear right: 746 mm

Test objective: Car to FWDB test.

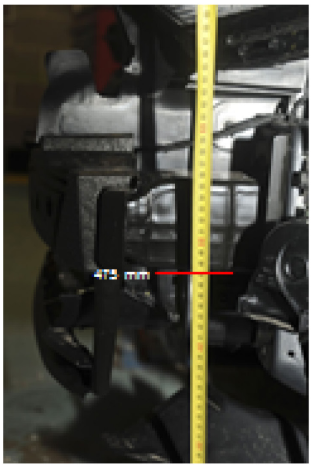
Full Frontal FWDB impact test on SUV 2

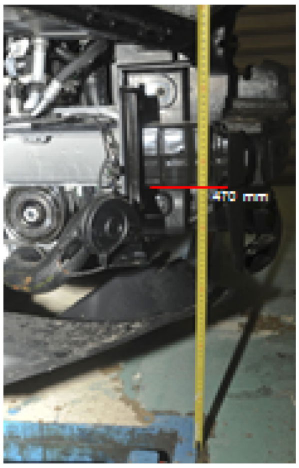
Structural analysis

IDIADA test no. 123514FF

Vehicle: SUV 2

Ground clearance: 475 mm to bumper beam CTR bottom





Full Frontal FWDB impact test on SUV 2

Test conditions

IDIADA test no. 123514FF

Vehicle: SUV 2

Test Vehicle Mass: 1846.0 kg

Test velocity: 56.54 km/h

Ground clearance: 475 mm to bumper beam CTR bottom

SUMMARY		
Head and Neck assessment	4,000	4,000
Chest assessment	2,840	2,349
Knee, Femur and Pelvis assessment	3,924	1,673
Lower Leg, Foot and Ankle Assessment	2,888	2,922
TOTAL	13,653	10,944
Door Opening	0,00	
TOTAL FRONTAL	10,944	

SUV 2 FWDB Impact

Pre-Test photos

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SUV 2 FWDB Impact
Static measurement results

- No door opening during the test.
- No door opening after the test.

A-Pillar Left Top	3.2
A-Pillar Left Bottom	-1.0
B-Pillar Left Top	-3.8
B-Pillar Left Bottom	-2.2
A-Pillar Right Top	0.6
A-Pillar Right Bottom	-1.1
B-Pillar Right Top	3.7
B-Pillar Right Bottom	1.7
Steering Wheel	-63.3
Accelerator pedal	3.0
Brake pedal	0.5
Clutch pedal	-134.8

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SEVENTH FRAMEWORK PROGRAMME

SUV 2 FWDB Impact
Dummy results

SUV 2

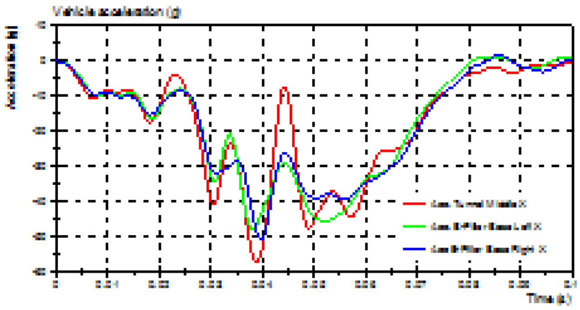
		Points		Points
HEAD				
Peak resultant acceleration - g	70,44	4,000	66,85	4,000
HIC_{15}	751,04		588,88	
Resultant Acc. 3 msec exceedence - g	66,63		67,48	
Unstable airbag contact, Bottoming out or Hazardous depl		0,000		0,000
Steering wheel displacement (-1) mm	-4	0,000		
Incorrect airbag deployment		0,000		0,000
Head Assessment		4,000		4,000
NECK				
Shear level exceeded - kN	0,37	4,000	0,39	4,000
duration of exceedence - ms	0		0,00	
Tension level exceeded - kN	1,75	4,000	1,07	4,000
duration of exceedence - ms	0		0,00	
Extension - Nm	36,40	4,000	36,89	4,000
Neck Assessment		4,000		4,000
Head and Neck Assessment		4,000		4,000
CHEST				
Compression - mm	30,12	2,840	33,38	2,349
Viscous criterion - m/s	0,14	4,000	0,36	4,000
Steering wheel contact (-1)		0,000		
A-Pillar displacement (-2) mm		0,000		
Unstable passenger compartment (-1)		0,000		
Shoulder belt load - kN	4,79		4,80	
Chest Incorrect Airbag Deployment Modifier		0,000		0,000
Chest Assessment		2,840		2,349

KNEE, FEMUR and PELVIS				
Left Knee Slide - mm	1,4	4,000	0,1	4,000
Left Femur Compression level exceeded - kN	0,71	4,000	1,1	4,000
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Left Knee, Femur and Pelvis Assessment		4,000		4,000
Right Knee Slide - mm	6,2	3,908	0,0	4,000
Right Femur Compression level exceeded - kN	2,78	4,000	6,5	1,979
duration of exceedence - ms	0		0,0	
Variable contact (-1)		0,000		0,000
Concentrated loading (-1)		0,000		0,000
Incorrect airbag deployment		0,000		0,000
Right Knee, Femur and Pelvis Assessment		3,908		1,979
Knee, Femur and Pelvis assessment		3,954		1,979
LOWER LEG				
Left compression - kN	2,54	3,640	2,15	3,800
Left Upper Tibia Index	0,65	2,888	0,91	3,811
Left Lower Tibia Index	0,35	4,000	0,37	3,246
Brake pedal vertical (-1) mm	-63	0,000		
Left Lower Leg assessment		2,888		3,246
Right compression - kN	1,90	4,000	2,29	3,847
Right Upper Tibia Index	0,37	4,000	0,71	3,622
Right Lower Tibia Index	0,41	3,928	0,71	3,622
Brake pedal vertical (-1) mm	-63	0,000		
Right Lower Leg assessment		3,928		3,622
FOOT and ANKLE				
Brake pedal horizontal displacement - mm	-68	4,000		
Footwell Rupture (-1)		0,000		
Pedal Blocking (-1)	22	0,000		
Foot and Ankle assessment		4,000		
Lower Leg Foot and Ankle assessment		2,888		2,622

SUV 2 FWDB Impact
Vehicle pulse

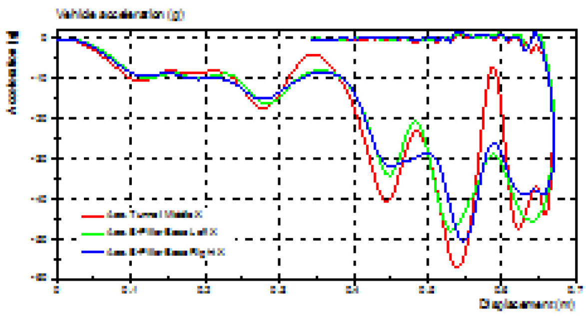
Time

B-Pillar Left side

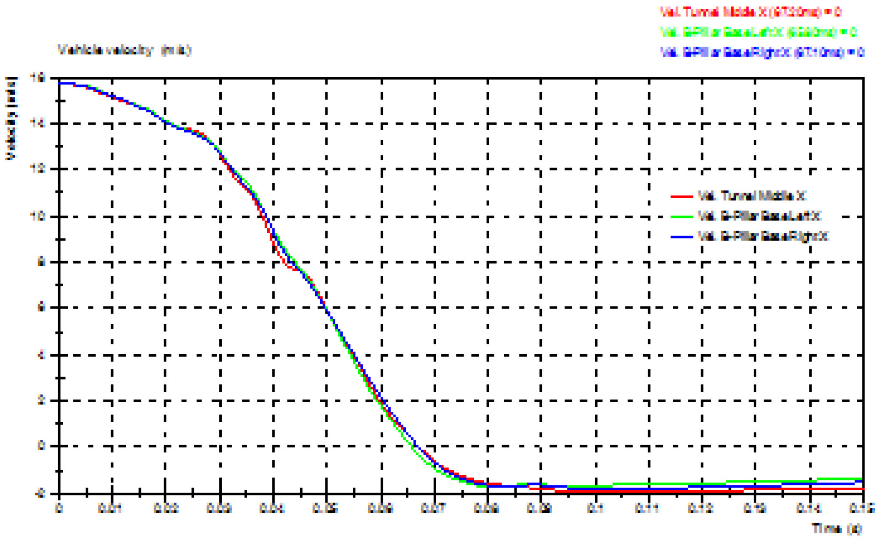


Displacement

B-Pillar Left side



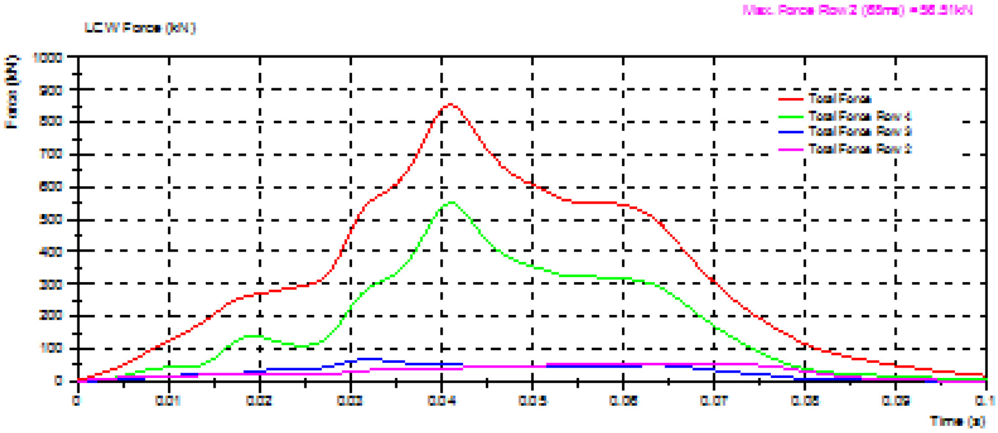
SUV 2 FWDB Impact
Vehicle velocity



SUV 2 FWDB Impact
LCW Force

Time

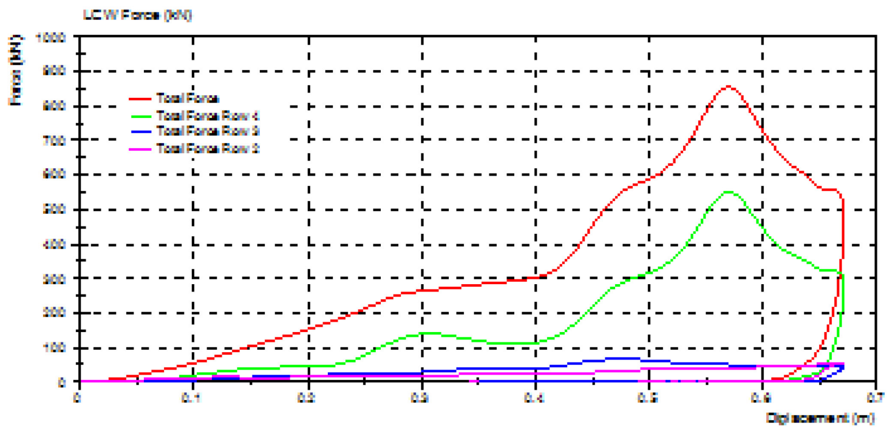
Max. LCW Force (41ms) = 853.75kN
Max. Force Row 4 (41ms) = 550.84kN
Max. Force Row 3 (33ms) = 68.05kN
Max. Force Row 2 (65ms) = 56.51kN



SUV 2 FWDB Impact
LCW Force

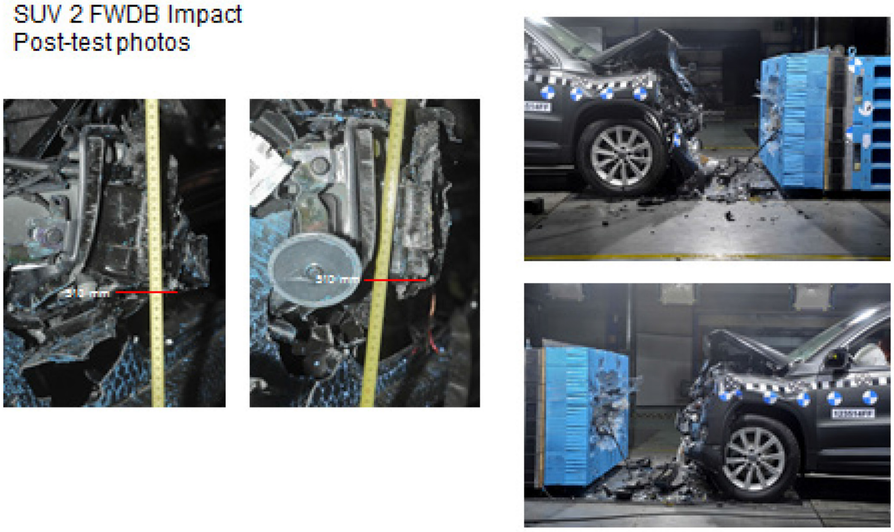
Displacement

B-Pillar Left side



SUV 2 FWDB Impact
Post-test photos

SUV 2 FWDB Impact
Post-test photos



SUV 2 FWDB Impact
Metrics

LCW forces at time of 40 ms
FT = 836.57 kN
F2 = 39.02 kN
F3 = 50.23 kN (6.0%)
F4 = 534.44 kN (63.8%)
F5 = 102.40 kN

Metric up to time of 40 ms
0.2 x FT40 = 334.62 kN

F3 = 66.05 kN	**FAIL**
F4 = 534.44 kN	**PASS**

Limit Reduction

F2 = 56.51 kN	Below 70 kN

Modified Metric

- Up to time of 40 msec
  - F4 + F3 ≥ [MIN(200, 0.4F_{T40})kN
  - F4 ≥ [MIN(100, 0.2F_{T40})kN
  - F3 ≥ [MIN((100-LR), (0.2F_{T40}-LR)) kN
  - where:
    - F_{T40} = Maximum of total LCW force up to time of 40 msec
    - Limit Reduction (LR) = [F2-70] kN and 0 kN ≤ LR ≤ 50 kN

SUV 2 FWDB Impact
Conclusions

- SUV 2 FWDB impact with 56 km/h in standard configuration (not raised)
- The rails were in alignment with row 4 and produces there the main amount of forces at the LCW (more than 50 %)
- The SUV 2 was in standard configuration, however it does not fulfill the geometric requirement of stage of the US voluntary agreement (rails too high)
- The SUV 2 failed the FWDB metrics as it should
- Dummy injury values were below R94 limits, maximum acceleration 55 g

SMALL FAMILY CAR 1 FWDB 56 KM/H @ BAST

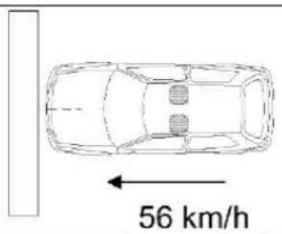
Small Family Car 1
FWDB 56 km/h
Test No. FM07RMFW

Thorsten Adolph
Tobias Langner

FIMCAR WP 3, 24th September 2012

FWDB Small Family Car 1

Test Date	15/06/2012
Location	BASt
Topic	FWDB Test
Test Number	**FM07RMFW**
Test Protocol	Draft FWDB protocol v1.doc



Vehicle 1:	Small Family Cars 1	Barrier:	FWDB barrier (750mm)
Brand/type	(silver)		
Impact side:	Front		
Speed:	56,02 km/h		
Overlap:	100 %	Impact accuracy	8 mm left 0 mm
Test mass:	1441 kg		
Dummy:	LHS – Hybrid III 50th RHS – Hybrid III 5th	Barrier ground clearance	80 mm
		LCW / barrier dimensions	2000 mm wide 750 mm high 300 mm deep

Test objectives: To complete the test data set for the FWDB approach; to add additional data and compare with previous tests (e.g. Renault Megane vs. Renault Koleos)

Small Family Car 1, FWDB 56 km/h, FM07RMFW

Test parameters

- Vehicle data: Small Family Car 1(Left hand drive)
- Vehicle identification no (VIN):
- Engine / Transmission: Diesel, manual transmission
- Test speed: 56,02 km/h
- Test weight: 1441 kg
- Test impact accuracy: 0 mm, 10 mm up

- Test vehicle status:
  - No changes in ride height

FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Pre-test Pictures Vehicle

FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

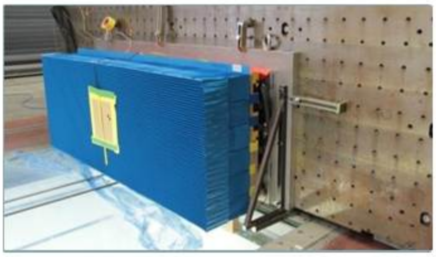
Pre-test Pictures Vehicle

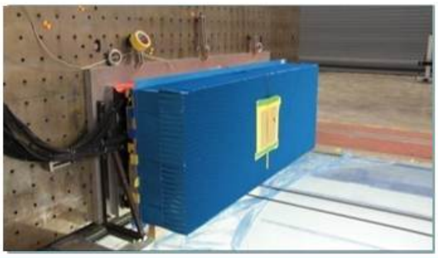
Small Family Car 1, FWDB 56 km/h, FM07RMFW

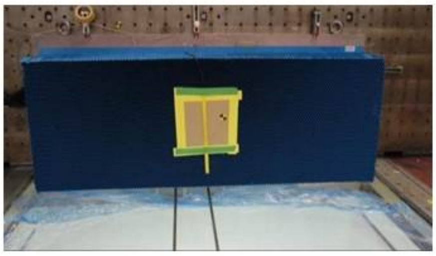
Pre-test Pictures Dummy

Small Family Car 1, FWDB 56 km/h, FM07RMFW

Pre-test Pictures
Barrier / Trolley





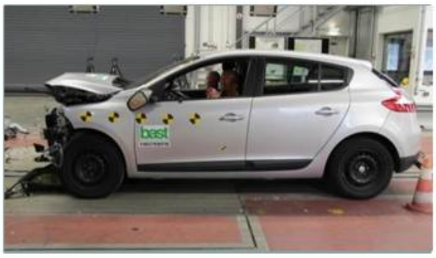


FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Vehicle Overview



FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Vehicle Structure

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures
Barrier

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Post-test Pictures Dummy




FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Small Family Car 1 front end structure

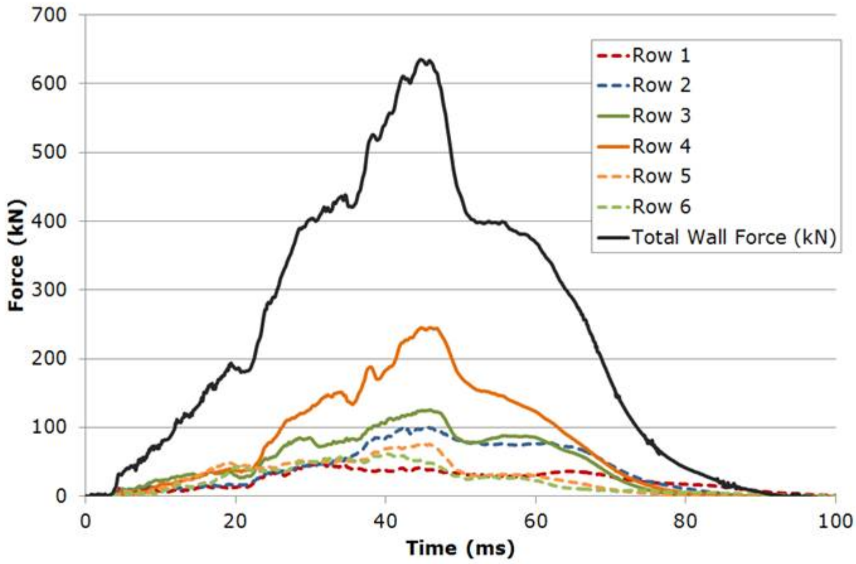
HIGHER CROSSBEAM				LOWER CROSSBEAM (middle plane)				CRUSH CAN	
Top height	Bottom height	Depth	Distance from the wheel axis centre	Top height	Bottom height	Depth	Distance from the wheel axis centre	Bottom height	Top Height
503	411	40	627	277	232	54	588	227	278

FIMCAR frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Plot: Row forces over time



Small Family Car 1, FWDB 56 km/h, FM07RMFW

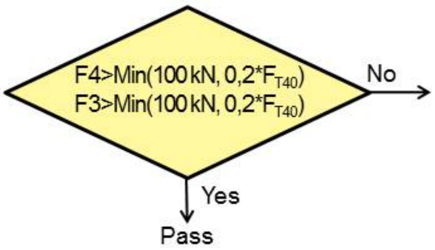
Metrics evaluation

Upgrade1 FWDB: up to 40 ms

→F3 > [MIN(100, 0.2Ft40)] AND

→F4 > [MIN(100, 0.2Ft40)]

	Megane FWDB		
	Value kN	0.2*Ft40	OK/NO
F3 > MIN[100, 0.2Ft40]	107	109	OK
F4 > MIN[100, 0.2Ft40]	188	109	OK
Global	OK		
LR [F2-70kN]	F2 = 85.3kN; LR = 15,3 kN		

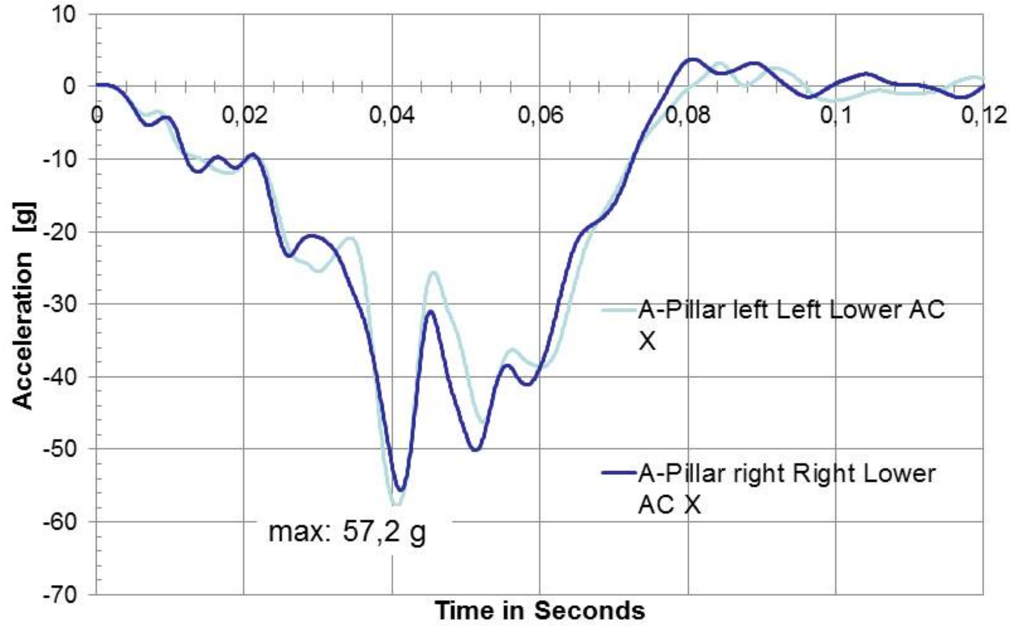


Modified Metric

- Up to time of 40 msec
  - $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
  - $F4 \geq [MIN(100, 0.2F_{T40})$ kN
  - $F3 \geq [MIN((100\text{-}LR), (0.2F_{T40}\text{-}LR))$ kN
  - where:
    - F_{T40} = Maximum of total LCW force up to time of 40 msec
    - Limit Reduction (LR) = [F2-70] kN and 0 kN ≤ LR ≤ 50 kN

Small Family Car 1, FWDB 56 km/h, FM07RMFW

Plot: Vehicle acceleration (x, a pillar)

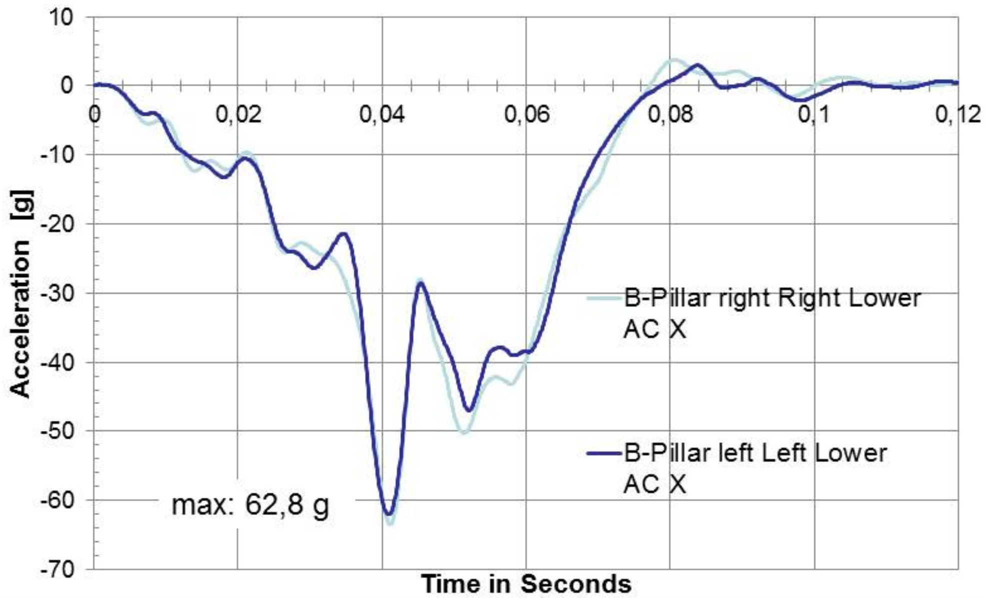


FIMCAR
frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

SEVENTH FRAMEWORK PROGRAMME

Plot: Vehicle acceleration (x, B-pillar)

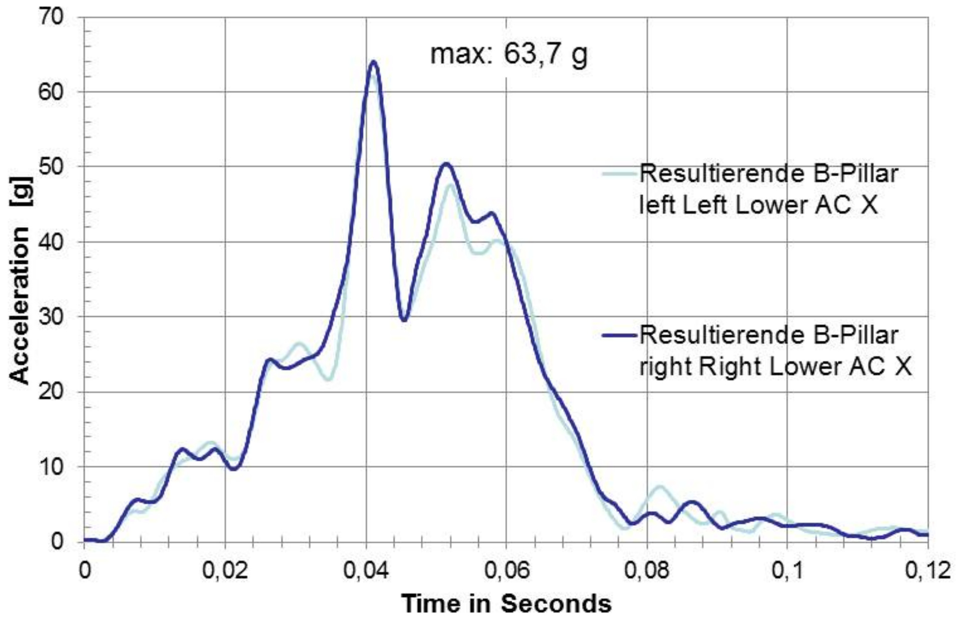


FIMCAR
frontal impact and compatibility assessment research

Small Family Car 1, FWDB 56 km/h, FM07RMFW

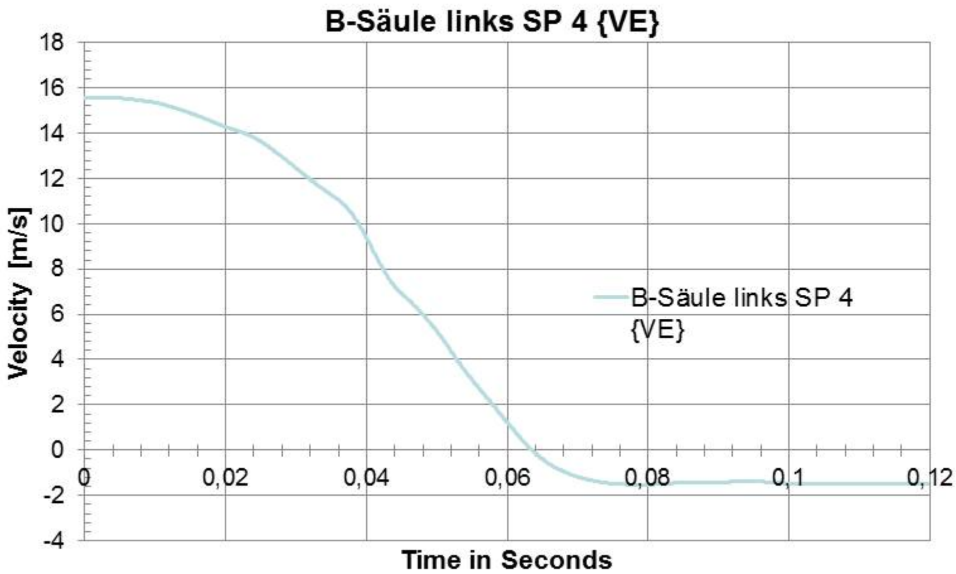
SEVENTH FRAMEWORK PROGRAMME

Plot: Vehicle acceleration (Res, B-pillar)



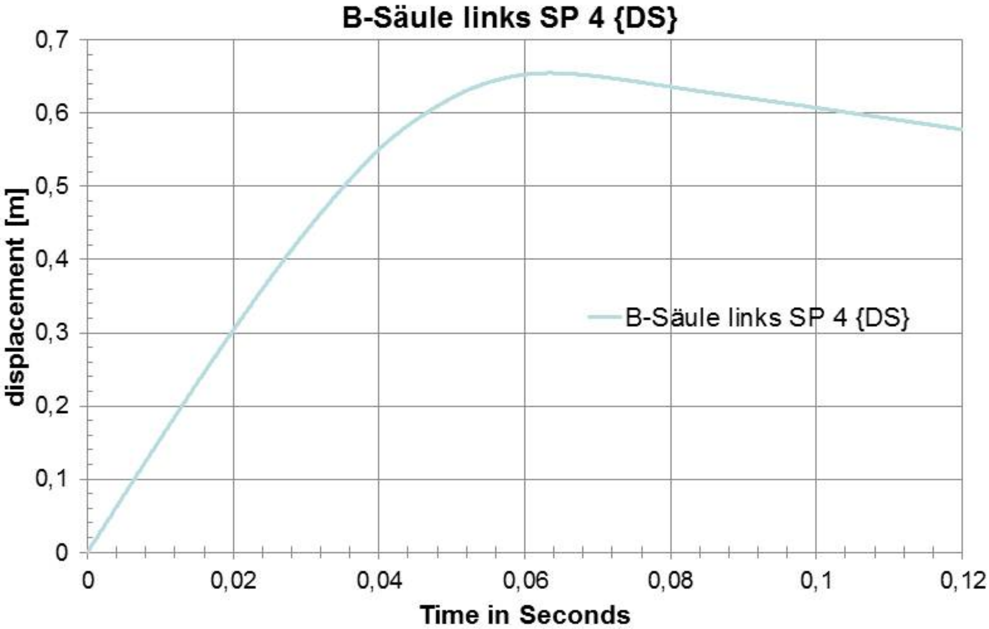
Small Family Car 1, FWDB 56 km/h, FM07RMFW

Plot: Vehicle velocity (b pillar)



Small Family Car 1, FWDB 56 km/h, FM07RMFW

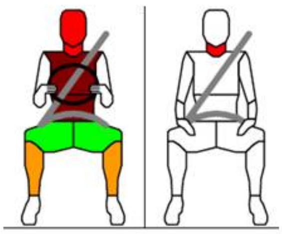
Plot: Vehicle displacement (b pillar)



Dummy values FWDB Test

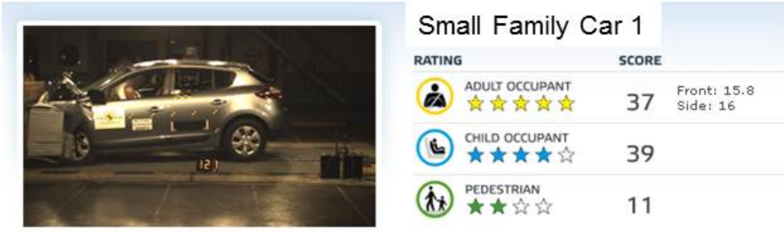
Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (HF)		
Head & Neck			0.000			0.000
Head						
HIC 36	2670.91		0.000	3069.15		
Acceleration Resultant	155.55	g		231.46	g	
3ms cumulative	142.93	g	0.000	159.32	g	
Neck						
Shear Force Fx+	0.24	kN	4.000	1.21	kN	0.000
Shear Force Fx-	-3.30	kN	0.000	-0.79	kN	0.000
Tensile Force Fz+	9.43	kN	0.000	2.66	kN	0.000
Extension My-	-86.66	Nm	0.000	-38.40	Nm	
Chest			0.915			
Deflection	-43.60	mm	0.915	-24.94	mm	
VC max	0.40	m/s	4.000	0.25	m/s	
belt at upper diagonal belt Force	4.28	kN		4.46	kN	

The restraint system was not fired!



Criterion	Driver SP 1 (H3)			Co-Driver SP 3 (HF)	
Femur & Knee			4.000		
Left					
Femur Force Fz-	-0.57	kN	4.000		
Knee Slider Displacement	-1.61	mm	4.000		
Right					
Femur Force Fz-	-2.17	kN	4.000		
Knee Slider Displacement	-5.35	mm	4.000		
Tibia			2.300		
Left					
Compression Upper Fz-	-2.81	kN	3.459	-2.37	kN
Compression Lower Fz-	-2.77	kN	3.484	-2.74	kN
Tibia Index Upper	0.72		2.598	0.94	
Tibia Index Lower	0.67		2.808	0.32	
Right					
Compression Upper Fz-	-4.12	kN	2.586	-1.80	kN
Compression Lower Fz-	-4.55	kN	2.300	-2.05	kN
Tibia Index Upper	0.76		2.398	1.50	
Tibia Index Lower	0.44		3.837	0.59	

Dummy values Euro NCAP Test



Conclusions

- Small Family Car 1 tested with 56 km/h against FWDB
- The vehicle has two load paths
  - Longitudinals which are located in row 3 and 4
  - Subframe with a crossbeam in height of row 2
- The Small Family Car 1 has its main rails slightly higher than would be ideal to meet the original metric requirements easily but because it has a lower load path the modified metric allows it to have its rails at this height and still meet the metric requirements easily
- Max vehicle acceleration: 52 g
- The restraint system was not activated during the test

Small Family Car 1, FWDB 56 km/h, FM07RMFW

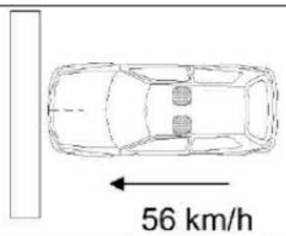
SUPERMINI 2 FWDB 40 KM/H @ BAST

Supermini 2
FWDB 40 km/h
Test No. FM08F5FW

Thorsten Adolph

FIMCAR WP 3, 20th September 2012

FWDB Supermini 2



56 km/h

Test Date Location Topic Test Number Test Protocol	07/09/2012 BASt FWDB Test **FM08F5FW** Draft FWDB protocol v1.doc	Vehicle 1: Brand/type Impact side: Speed: Overlap: Test mass: Dummy:	Supermini 2 (black) Front 39,96 km/h 100 % 1106 kg LHS – Hybrid III 50th RHS – Hybrid III 5th	Barrier: Impact accuracy Barrier ground clearance LCW / barrier dimensions	FWDB barrier (750mm) 35 mm left 18 mm 80 mm 2000 mm wide 750 mm high 300 mm deep

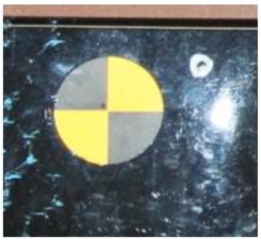
Test objectives:
To investigate the changes of the FWDB metric with a lower test speed
To investigate the dummy performance with a lower test speed

Supermini 2, FWDB 40 km/h, FM08F5FW

Test parameters

- **Vehicle data: Supermini 2 (Left hand drive)**
- **Vehicle identification no (VIN):**
- **Engine / Transmission: 1,2 l, manual transmission**
- **Test speed: 39,96 km/h**
- **Test weight: Front 664 kg / Rear 442 Total 1106 kg**
- **Test impact accuracy: 85 mm left, 18 mm up**

- **Test vehicle status:**
  - **Normal ride height but adjusted to previous Supermini 2 test at FIAT**



Supermini 2, FWDB 40 km/h, FM08F5FW

Ride Height

	Front		Rear	
	Left	**Right**	**Left**	**Right**
Supermini 2 BASt (50 km/h)	625	628	628	631
Supermini 2 Fiat (56 km/h)	627	628	634	636

Supermini 2, FWDB 40 km/h, FM08F5FW

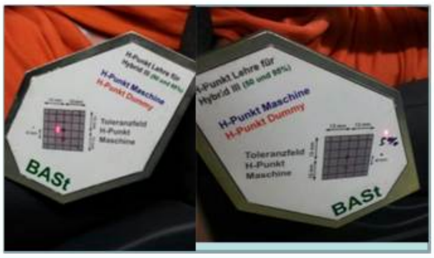
Pre-test Pictures Vehicle

Supermini 2, FWDB 40 km/h, FM08F5FW

Pre-test Pictures Vehicle

Supermini 2, FWDB 40 km/h, FM08F5FW

Pre-test Pictures Dummy

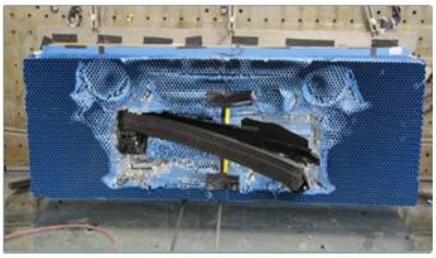


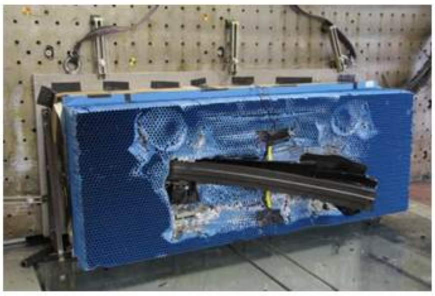
Supermini 2, FWDB 40 km/h, FM08F5FW

Post-test Pictures Vehicle Overview

Supermini 2, FWDB 40 km/h, FM08F5FW

Post-test Pictures
Barrier





Supermini 2, FWDB 40 km/h, FM08F5FW

Post-test Pictures Dummy

Supermini 2, FWDB 40 km/h, FM08F5FW

Front end structure

Dimensions [mm]	Top height	Bottom height	Width	Depth
Engine	737	167	470	263
Gear Box	370	160	372	-
PEAS	514	401	-	-

Three front load paths

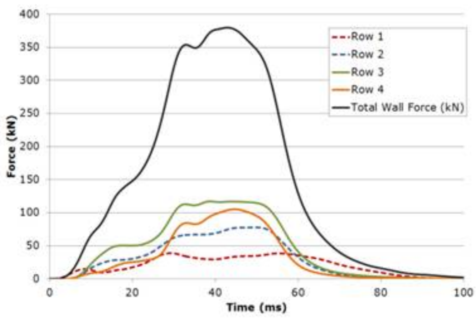
- *Upper load path: Frontend assembly/radiator support at bonnet leading edge*
- *Lower load path: Longitudinals / crush can/ bumper crossbeam → PEAS*
- *3rd load path: Sub frame/crush can/crossbeam → SEAS*
- *Vertical connection between all load paths*

FIMCAR frontal impact and compatibility assessment research | Supermini 2, FWDB 40 km/h, FM08F5FW | SEVENTH FRAMEWORK PROGRAMME

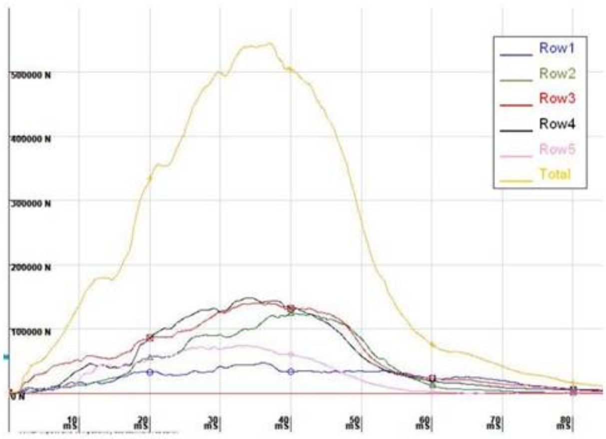
Plot: Row forces over time

40 km/h FWDB

Peak forces up to 40ms:
Total = 376kN
Row 1 = 38.8kN
Row 2 = 68.7kN
Row 3 = 117.0kN
Row 4 = 97.7kN



56 km/h FWDB



FIMCAR frontal impact and compatibility assessment research | Supermini 2, FWDB 40 km/h, FM08F5FW | SEVENTH FRAMEWORK PROGRAMME

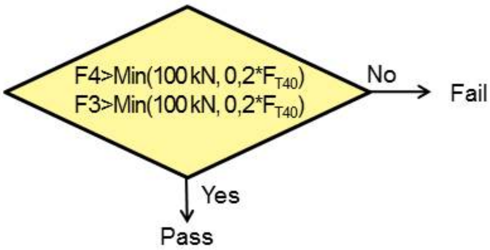
Metrics evaluation

40 km/h FWDB

	Supermini 2 40km/h		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	117	75.3	OK
F4 > MIN[100, 0.2Ft40]	97.7	75.3	OK
Global	OK		

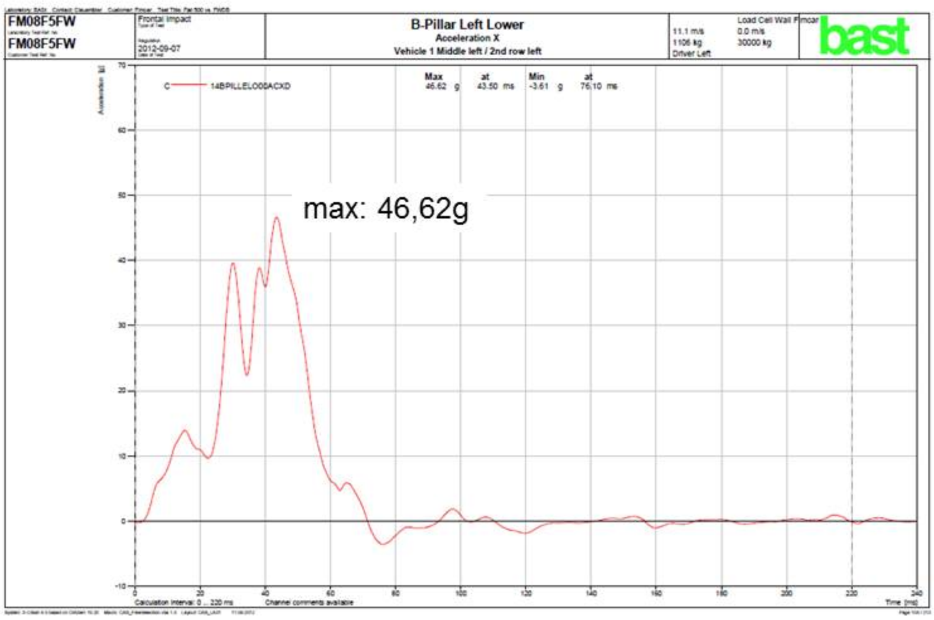
56 km/h FWDB

	Supermini 2 FWDB 56 km/h		
	Value	0.2*Ft40	OK/KO
F3 > MIN[100, 0.2Ft40]	140.1	108.7	OK
F4 > MIN[100, 0.2Ft40]	148.1	108.7	OK
Global	OK		



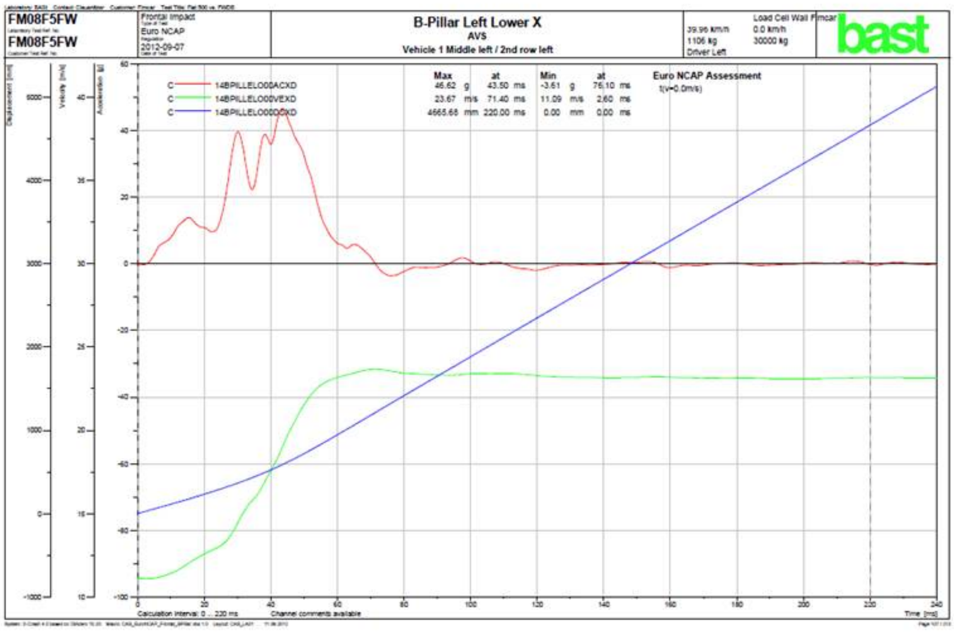
Supermini 2, FWDB 40 km/h, FM08F5FW

Plot: Vehicle acceleration (x, B-pillar)



Supermini 2, FWDB 40 km/h, FM08F5FW

Plot: Vehicle velocity / displacement (b pillar)

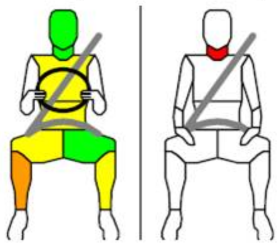


Supermini 2, FWDB 40 km/h, FM08F5FW

SEVENTH FRAMEWORK PROGRAMME

Dummy values

Criterion	Driver SP 1 (H3)	Co-Driver SP 3 (HF)
Head & Neck	4.000 *	0.000 *
Head		
HIC 36	718.07	1119.39
Acceleration Resultant	76.13 g 4.000 *	88.03 g
3ms cumulative	74.39 g	86.79 g
Neck		
Shear Force Fx+	0.76 kN 4.000 *	0.41 kN 0.000 *
Shear Force Fx-	-0.25 kN 4.000 *	-0.41 kN 0.000 *
Tensile Force Fz+	1.28 kN 4.000 *	0.66 kN 0.000 *
Extension My-	-14.03 Nm 4.000 *	-18.28 Nm
Chest	3.321 *	
Deflection	-26.75 mm 3.321 *	-20.51 mm
VC max	0.16 m/s 4.000 *	0.18 m/s
belt at upper diagonal belt Force	3.44 kN	3.63 kN



Criterion	Driver SP 1 (H3)	Co-Driver SP 3 (HF)
Femur & Knee	3.657 *	
Left		
Femur Force Fz-	-0.54 kN 4.000 *	
Knee Slider Displacement	-0.14 mm 4.000 *	
Right		
Femur Force Fz-	-3.69 kN 4.000 *	
Knee Slider Displacement	-6.77 mm 3.657 *	
Tibia	2.128 *	
Left		
Compression Upper Fz-	-1.61 kN 4.000 *	-1.45 kN
Compression Lower Fz-	-1.93 kN 4.000 *	-1.72 kN
Tibia Index Upper	0.52 3.483 *	0.44
Tibia Index Lower	0.37 4.000 *	0.65
Right		
Compression Upper Fz-	-4.07 kN 2.618 *	-1.20 kN
Compression Lower Fz-	-4.81 kN 2.128 *	-1.56 kN
Tibia Index Upper	0.52 3.445 *	0.80
Tibia Index Lower	0.45 3.778 *	0.72
Sum	13.106	(0.000)

Supermini 2, FWDB 40 km/h, FM08F5FW

SEVENTH FRAMEWORK PROGRAMME

Dummy values Euro NCAP Test

SUMMARY Supermini 2

Adult Occupant Rating

Frontal Driver	
Head and Neck assessment	4.00
Chest assessment	3.82
Knee, Femur and Pelvis assessment	4.00
Lower Leg, Foot and Ankle assessme	3.29
Frontal Passenger	
Head and Neck assessment	4.00
Chest assessment	3.94
Knee, Femur and Pelvis assessment	4.00
Lower Leg assessment	3.84
Door Opening	0
OVERALL FRONT	15.11

Conclusions

- High head acceleration for the 5% HIII Dummy on the passenger seat due to airbag deployment
- Higher loading of the lower extremity for the driver compared to the Euro NCAP test
- Maximum vehicle acceleration of 46 g

- Vehicle has a far forward located lower load path. However it passes the metric in the 56 km/h test.
- In this 40 km/h test the vehicle passes as well the FWDB metric even without the need of a lower limit reduction

Supermini 2, FWDB 40 km/h, FM08F5FW

Jeroen Uittenbogaard, Ton Versmissen

FIMCAR
IX – MDB Test Procedure: Initial Test Protocol

The FIMCAR project was co-funded by the European Commission under the 7th Framework Programme (Grant Agreement no. 234216).

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CONTENT

EXECUTIVE SUMMARY

This protocol describes the Mobile Progressive Deformable Barrier test. The MPDB protocol is derived from the PDB test protocol developed by UTAC [Edwards 2006/1], the FWDB test and assessment protocol developed by TRL [Edwards 2006/2], the Euro NCAP frontal impact testing protocol [Euro NCAP 2009] and ECE regulation No. 94 [ECE 2009]. The protocol describes a test between the test car and a 1500 kg moving trolley with a closing speed of 100 km/h. The off-set for the test car is 50% of the vehicle width. The trolley is equipped with a PDB deformable barrier face. Especially trolley weight and closing speed are subject to further analysis in order to define the test severity at an appropriate level for the existing range of vehicles. The objective of the test procedure is to assess the self- and partner protection, also known as compatibility.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self and partner-protection level) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition, another procedure (tests with a moving deformable barrier) is under discussion in today's research programmes.

Within the FIMCAR project, different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

Unlike the off-set and full overlap test procedures for frontal impact, a test protocol is not fixed for the frontal moving deformable barrier test procedures. Therefore, a test and assessment procedure is developed to assess frontal compatibility.

1.3 Structure of this Deliverable

First the test configuration is explained, where relevant parameters are chosen. Next, a detailed description is given about how to prepare the vehicle for the test. Then anthropometric test devices preparation and positioning are described. Finally the assessment criteria are explained.

2 TEST CONFIGURATION

In this test the test vehicle is assessed with a moving trolley equipped with a deformable barrier face in a frontal configuration. The trolley itself represents the most probable collision partner in terms of vehicle mass. The deformable element of the trolley represents a corresponding stiffness of a modern vehicle.

The impact speed and overlap are based on accident data and currently existing test procedures.

2.1 Trolley Mass

The mass of the trolley is based on a Swedish data showing the cumulative distribution of the vehicle fleet of Sweden in 2008 and the EU in 2005 [SIKA]. Both distributions are in-line and give an average vehicle mass of 1500 kg, without occupants. This is also backed up by the AE-MDB (Advanced European Moving Deformable Barrier) side impact trolley mass, which is also set to 1500 kg [Ellway 2005].

Remark

This average mass of 1500 kg is the starting point for the MDB test within the FIMCAR project. Tests with other masses, between 1300 kg and 1800 kg, will be carried out to define the optimal mass for future MDB tests.

Occupant masses are not taken into account as the restraint system will spread this mass over time during a collision.

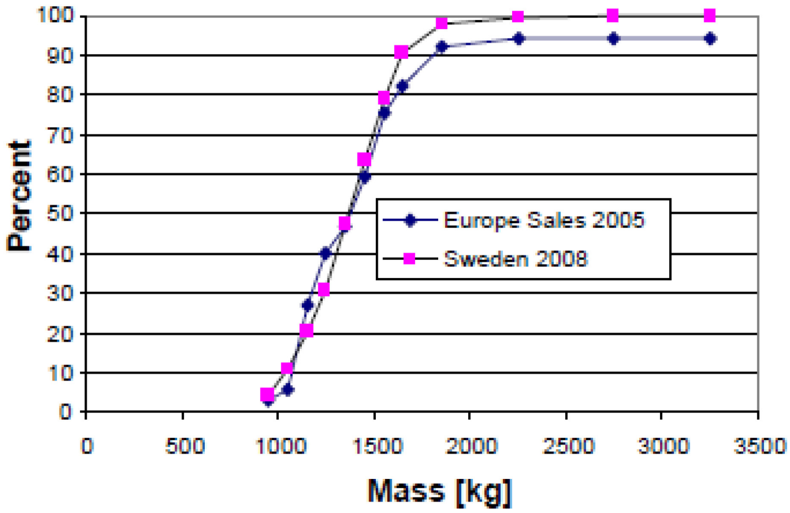

Figure 2.1: Vehicle mass distribution for Sweden and Europe [SIKA].

2.2 Deformable Barrier

The deformable barrier in front of the trolley also needs to represent the most common collision partner in terms of stiffness. Using a pragmatic approach, the already well developed Progressive Deformable Barrier (PDB) is chosen as the deformable barrier. How the PDB compares, in terms of overall stiffness, with the current European vehicle fleet is shown in *Figure 2.2*. The average force-deflection curve of 26 cars tested within Euro NCAP from 2006-2009 together with the PDB calibration corridor is shown. The assumption is made that the ODB is fully bottomed out before the car starts to deform and therefore the

PDB dynamic calibration corridor is shifted by the depth of the ODB (450mm). It can be seen that the average stiffness of the 26 cars is in line with the bottom end of the PDB calibration corridor.

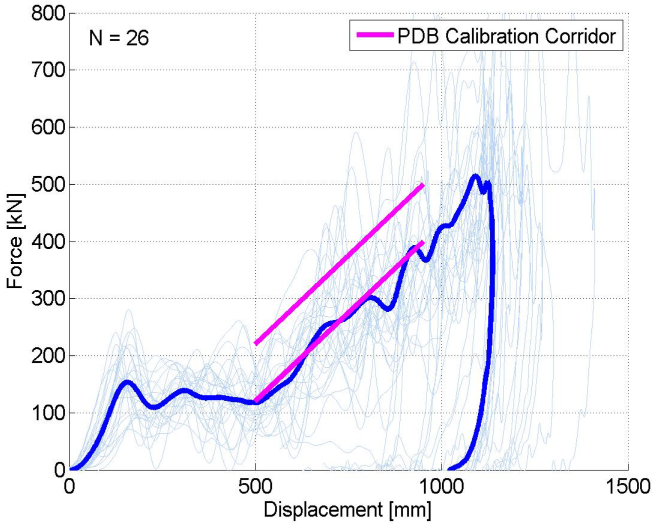

Figure 2.2: Average force-deflection curve of 26 cars tested within Euro NCAP from 2006 to 2009 together with the shifted PDB calibration corridor.

2.3 Impact Speed, Angle and Overlap

The impact speed, angle and overlap are based on real word accident data and existing test procedures.

The baseline situation for the current R94 is a frontal car-to-car collision with both vehicles travelling at 50 km/h with an overlap of 50% and an impact angle of 0 degrees. To best represent this baseline situation, the single vehicle-to-barrier test was derived and set to 56 km/h, an overlap of 40% with an impact angle of zero degrees.

Figure 2.3 shows the closing speed of front-to-front car collisions based on recent accident data. A closing speed of 100km/h, in-line with the baseline test, will cover 90% of the frontal car-to-car collisions in terms of speed [Data from GIDAS holding accidents from the Hannover and Dresden area in between 1999 to 2009 with no restriction on car model/age. Only front-to-front car-to-car crashes are included where the direction of force during the collision is in between 11, 12 and 1 o'clock. MAIS has been calculated on the basis of the maximum MAIS of all occupants of the subject car. Both cars are within 600 to 3500 kg curb weight and all collisions have an impact speeds below 150 km/h].

Within the VC-Compat project all car-to-car tests were performed with a closing speed of 112 km/h. This higher closing speed will only cover 4% more cases as shown in Figure 2.3.

One single MPDB-to-car test performed at a closing speed of 112 km/h using a small car showed that this test speed is very severe. Other MPDB tests at a closing speed of 90 km/h (covering around 85%) have shown that the severity is low and will not result in adjusted vehicle design. (To further investigate and fix the test speed another test with the Small Family Car 2 will be performed at a closing speed of 112 km/h.)

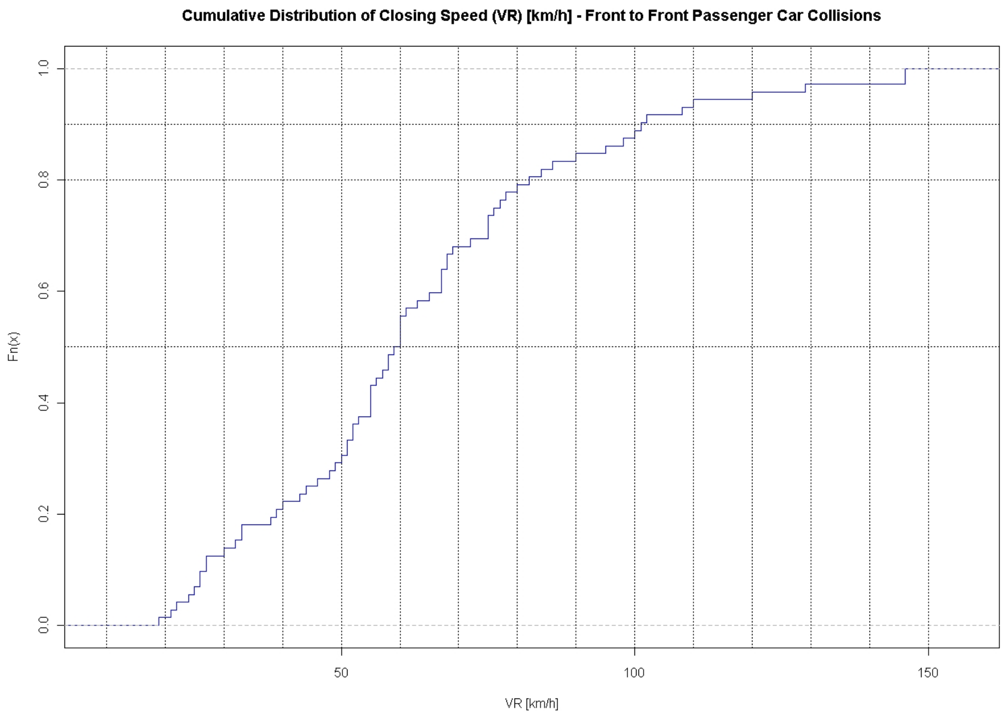

Figure 2.3: Cumulative distribution of closing speed in front to front collisions with MAIS 3+ and fatal injuries.

2.4 Proposed Test Set-Up

In summary the following test set-up is proposed.

Trolley mass: 1500 kg
starting point; some test with masses between 1300 and 1800 kg

Deformable barrier: PDB-XT

Trolley speed: 50 km/h (to be determined; limits 45 – 56 km/h)

Vehicle speed:50 km/h (to be determined; limits 45 – 56 km/h)

Overlap: 50%

Angle: 0 degrees

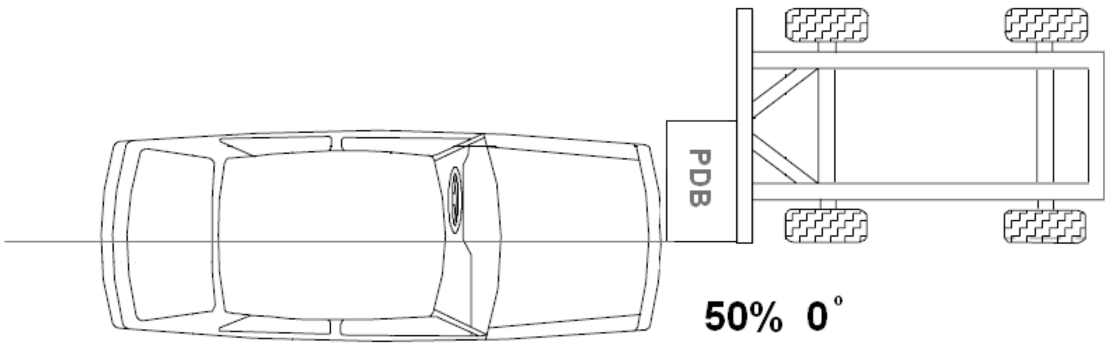

Figure 2.4: Test set-up.

3 VEHICLE PREPARATION

The test mass is defined identical as can be found in the Euro NCAP test protocol [Euro NCAP 2009]:

3.1 Unladen Kerb Mass

3.1.1 The capacity of the fuel tank will be specified in the manufacturer's booklet. This volume will be referred to throughout as the "fuel tank capacity".

3.1.2 Syphon most of the fuel from the tank and then run the car until it has run out of fuel.

3.1.3 Calculate the mass of the fuel tank capacity using a density for petrol of 0.745g/ml or 0.840g/ml for diesel. Record this figure in the test details.

3.1.4 Put water, or other ballast, to this mass in the fuel tank.

3.1.5 Check the oil level and top up to its maximum level if necessary. Similarly, top up the levels of all other fluids to their maximum levels if necessary.

3.1.6 Ensure that the vehicle has its spare wheel on board along with any tools supplied with the vehicle. Nothing else should be in the car.

3.1.7 Ensure that all tires are inflated according to the manufacturer's instructions for half load.

3.1.8 Measure the front and rear axle weights and determine the total weight of the vehicle. The total weight is the 'unladen kerb mass' of the vehicle. Record this mass in the test details.

3.1.9 Measure and record the ride heights of the vehicle at all four wheels

3.2 Reference Loads

3.2.1 Calculate 10 percent of the fuel tank capacity mass as determined in 2.1.3

3.2.2 Remove this mass of ballast from the fuel tank, leaving 90 percent of the mass in the tank.

3.2.3 Place both front seats in their mid-positions. If there is no notch at this position, set the seat in the nearest notch rearward (this will be done more completely in Section 6).

3.2.4 Place a mass of equivalent to a Hybrid-III dummy (88kg with instrumentation and cables) on each of the front seats.

3.2.5 Place 36kg in the luggage compartment of the vehicle. The normal luggage compartment should be used i.e. rear seats should not be folded to increase the luggage capacity. Spread the weights as evenly as possible over the base of the luggage compartment. If the weights cannot be evenly distributed, concentrate weights towards the centre of the compartment.

3.2.6 Roll the vehicle back and forth to 'settle' the tyres and suspension with the extra weight on board. Weigh the front and rear axle weights of the vehicle. These loads are the "axle reference loads" and the total weight is the "reference mass" of the vehicle.

3.2.7 Record the axle reference loads and reference mass in the test details

3.2.8 Record the ride-heights of the vehicle at the point on the wheel arch in the same transverse plane as the wheel centers. Do this for all four wheels.

3.2.9 Remove the weights from the luggage compartment and the front and rear seats.

3.3 Vehicle Width and Overlap

3.3.1 Determine the widest point of the vehicle ignoring the rear-view mirrors, side marker lamps, tire pressure indicators, direction indicator lamps, position lamps, flexible mudguards and the deflected part of the tire side-walls immediately above the point of contact with the ground.

3.3.2 Record this width in test details.

3.3.3 Determine the centre-line of the vehicle.

3.4 Vehicle Painting

Paint the separate components from the bottom view in contrasting colours. This will give an insight in the translations, deformations and load paths of the separate components in the front end of the vehicle. An example is shown in Figure 3.1.

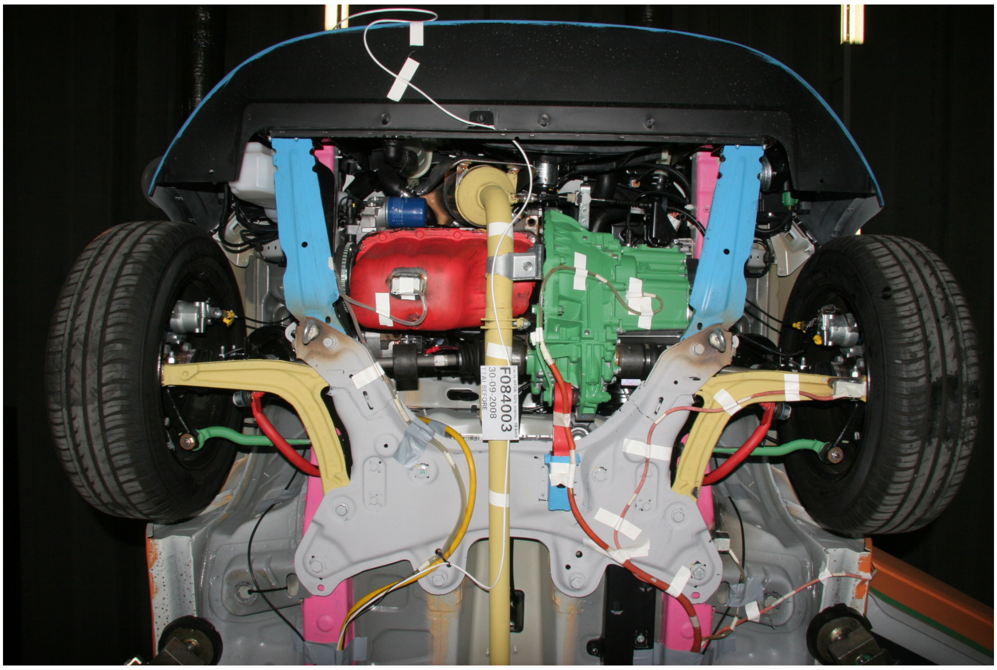

Figure 3.1: Vehicle painting.

3.5 Propulsion of Vehicle and Trolley

The test objects are propelled as per Regulation 94. This requires that the vehicle shall not be propelled by its own engine, that at the moment of impact the vehicle and trolley will not be subject to any external steering or propelling device. The relative impact accuracy can be checked by placing a small pin close to the edge of the barrier and mark the place where the pin should strike on the bumper of the car for which the given overlap is exactly achieved. The relative impact accuracy shall be within 25 mm laterally and 25 mm vertically out of line in either direction. The velocity accuracy shall within 0.5 km/h for both the vehicle and trolley.

3.6 Vehicle Marking

The vehicle shall be marked according to Figure 3.2.

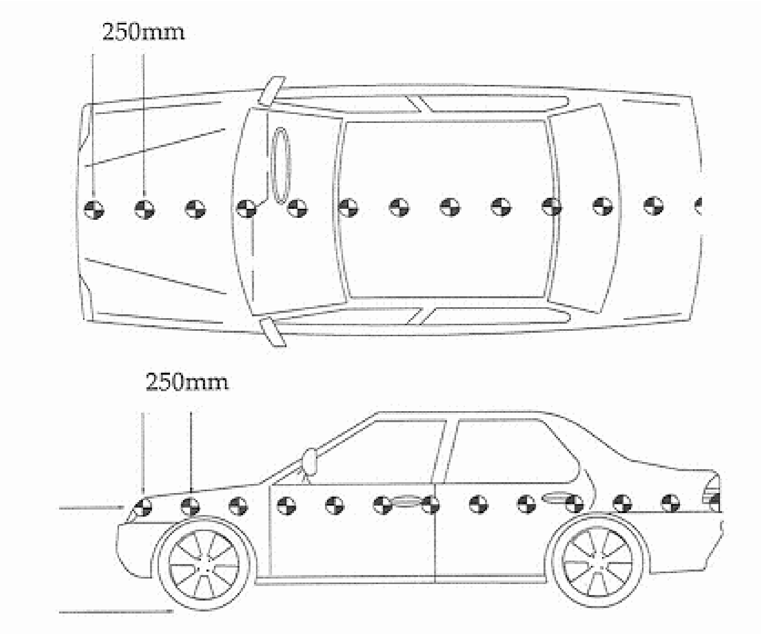

Figure 3.2: Vehicle marking.

3.7 Acceleration Measurements

In the following tables the locations of the accelerometers are given for the test vehicle (Table 1) and for the moving trolley (Table 2). For a right hand drive (RHD) car: left (L) becomes right (R).

Table 1: Accelerometer location in the vehicle.

Name	ISO-MME code	X	Y	Z
Engine Top central	10ENGNTP0000	x		
Engine bottom central	10ENGNBO0000	x		
Gear box bottom	10GEARBO0000	x		
Arm suspension LHS	11SUHOLO0000	x		
Turret LHS	11SUDO000000	x		
200 mm behind B-Pillar LHS	17CPILLO0000	x		
A-Pillar LHS	11APILBO0000	x		
Cross of the side member and the firewall	18FORAFRMI00	x		
B-Pillar RHS	16BPILLO0000	x	x	X
B-Pillar LHS	14BPILLO0000	x	x	X
Total		14		

Table 2: Accelerometer location on the trolley.

Name	ISO-MME code	X	Y	Z
CoG	?0MBARCG0000AC??	x	x	x
Frame left front CoG height	?0MBARLEFR00AC??	x	x	
Frame right front CoG height	?0MBARRIFR00AC??	x	x	
Frame left rear CoG height	?0MBARLERE00AC??	x	x	
Frame right rear CoG height	?0MBARRIRE00AC??	x	x	
Total		11		

4 DUMMIES

The dummy set-up is in line with R94 regulation, 2 instrumented Hybrid III 50 percentile on the front seats. The positioning of these dummies is in accordance with R94.

Table 3: Dummy (Hybrid III 50 percentile) instrumentation.

	Driver			Pas. Av.		
	X	Y	Z	X	Y	Z
Head acceleration	X	X	X	X	X	X
Neck upper force	X	X	X	X	X	X
Chest acceleration	X	X	X	X	X	X
Chest deflexion		X			X	
Pelvis acceleration	X	X	X	X	X	X
Femur left force		X			X	
Femur right force		X			X	
Femur left acceleration		X			X	
Femur right acceleration		X			X	
Knee slider right		X			X	
Knee slider left		X			X	
Tibia upper force right	X		X	X		X
Tibia upper moment right	X	X		X	X	
Tibia lower force right	X		X	X		X
Tibia lower moment right	X	X		X	X	
Tibia upper force left	X		X	X		X
Tibia upper moment left	X	X		X	X	
Tibia lower force left	X		X	X		X
Tibia lower moment left	X	X		X	X	
Seat belt at upper diagonal belt		X			X	
Seat belt at lap belt outside		X			X	
TOTAL		37			37	

Dummies performance must be in line with specifications of the regulations.

5 CAMERA POSITION

For research purposes within the FIMCAR project eight cameras, two detailed from each side (1,3), two side 45 degrees (2,4), two bottom (global and detail) (5,6), two from above (global and detail) (7,8) shall be used (see Figure 5.1). During the course of the project the final number of cameras will be determined based on test experience.

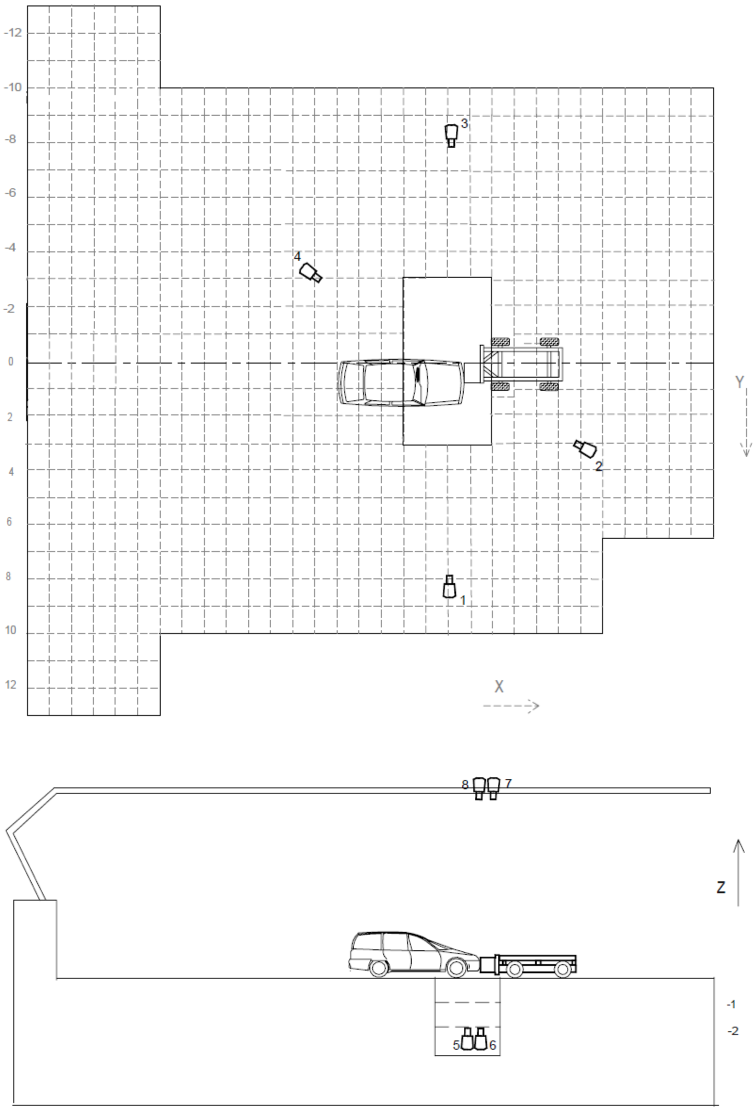

Figure 5.1: Initial proposal for camera positions.

6 STILLS

The following list is an altered version of the list given in the Euro NCAP frontal impact test protocol [Euro NCAP 2009].

No.	**View**
1.	Front view of barrier.
2.	Side view of barrier.
3.	Side view of barrier at 45 degrees to front.
4.	Side view of barrier with vehicle.
5.	Car RHS, with camera centred on junction of B-post waist, showing full car.
6.	Car RHS, with camera centred on B-post waist, showing rear passenger compartment.
7.	Car RHS, with camera aimed at waist height, showing driver's compartment.
8.	Car RHS at 45 degrees to front.
9.	Front view of car.
10.	Car LHS at 45 degrees to front.
11.	Car LHS, with camera aimed at waist height, showing front passenger's compartment.
12.	Car LHS, with camera centred on B-post waist, showing rear passenger compartment.
13.	Car LHS, with camera centred on B-post waist, showing full car.
14.	Top view of car
15.	Bottom view of car
16.	Driver and seat to show driver compartment and position of seat relative to the sill.
17.	To show area immediately in front of driver.
18.	To show driver's footwell area and location of dummy's feet and pedals.
19.	Passenger and seat to show compartment and position of seat relative to sill.
20.	To show area immediately in front of passenger.
21.	To show passenger footwell area and dummy's feet.
22.	*Overall view of where the car has come to rest after impact (including barrier).
23.	*To show position of all door latches and/or open doors.
24.	*To show driver knee contacts with facia (airbag should be lifted if obscuring view).
25.	*To show passenger knee contacts with facia (airbag should be lifted if obscuring view).

* Post-test only

7 MOVING TROLLEY

7.1 Trolley Design

The trolley dimensions are based on specifications of European vehicles which are presented in Table 4. The inertia properties of the trolley are based on the values given in the NHTSA database for a large range of vehicles [NHTSA 2013].

During the FIMCAR project two different trolleys will be used:

- A trolley especially developed by TNO and FTSS to carry out MDB tests, based on the Table 4 specifications.
- A side impact trolley, according to ECE R95 specifications, modified to carry out frontal MDB tests

The tests with both trolleys will be used to specify the need for a special designed trolley.

Table 4: Trolley specs.

Description	Value
Mass	1500 kg
Mass front axle	**1100 kg**
Mass rear axle	**400 kg**
Barrier face	PDB-XT
Barrier height	1.00 m
Barrier width	0.70 m
Barrier depth	0.70 m (0.80 m if extended)
Barrier ground clearance	150 mm
Barrier face location	Left or Right (depending on LHD or RHD) outlined with outside of wheels
Overall Length	4.25 m (4.35 m if extended)
Vehicle front to frontal axle	1.2 m (1.3 if extended)
Axle height	0.28 m
Wheel base	2.60 m
Track width	1.20 m
CoG x-dir (1)	1900 mm from front (2000 mm if extended)
CoG x-dir (2)	700 mm from frontal axle
CoG y-dir	0 (centre line)
CoG z-dir	600 mm from ground
Iyz Roll	550 kg*m^2 (representative of the 1500 kg vehicle)
Ixz Pitch	2550 kg*m^2 (representative of the 1500 kg vehicle)
Ixy Yaw	2650 kg*m^2 (representative of the 1500 kg vehicle)
Brakes	4 x disk brakes
Tyres	205/55 R15
Tyre pressure	2.5 bar
Load cell	48 x Light weight TSM

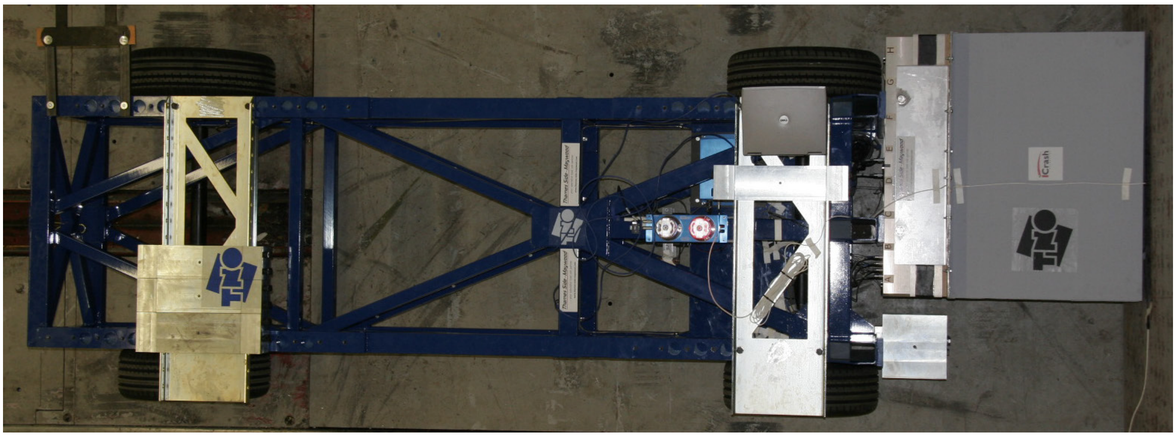

Figure 7.1: Overview picture of the trolley

8 ASSESSMENT

For analysing the test procedure FIMCAR will focus on structural interaction, vehicle response, intrusion measurements. The dummy readings will be analysed with lower priority. However, it is envisaged to propose dummy limits at the end of the analysis phase.

8.1 Self Protection

Vehicle accelerations in comparison with R94 procedures.

Dummy readings in comparison with R94 procedures

8.2 Partner Protection

MPDB assessment in accordance with PDB assessment procedures (under development):

- Digitisations of barrier
- Deformation/ intrusions
- Force measurements (F = m * $a_{trolley}$ or global force from LCW)

8.2.1 Digitisations of Barrier

A part of the partner protection is based on the barrier deformation. After crash the front face of the barrier is digitised in order to know the shape of the deformation. The file obtained from the digitisation is processed with appropriate PDB analysis software (e.g., PDBsoft, BDA etc. [FIMCAR 2013]). Some parameters are calculated automatically by the software such as the PPAD (Partner Protection Assessment from Deformation), AHOD (Average Height of Deformation and ADOD (Average Depth of Deformation) and the energy absorbed by the barrier in order to calculate the EES (equivalent energy speed).

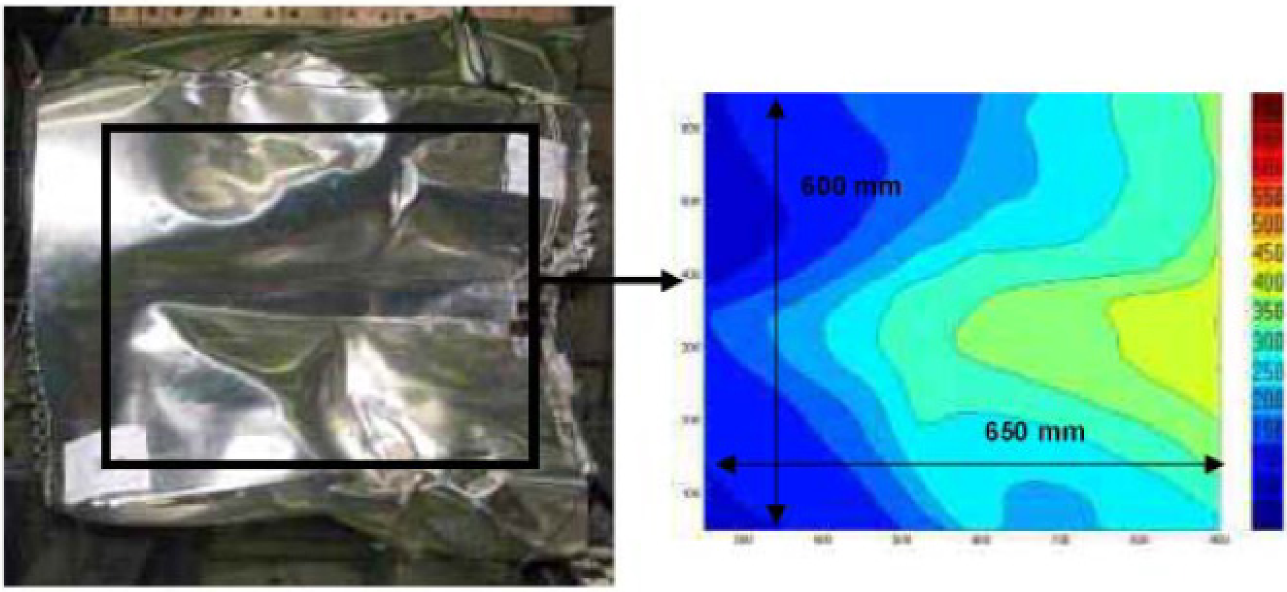

Figure 8.1: Barrier digitisation.

After having digitising the barrier shape, an assessment is made based on the deformation to be developed within FIMCAR WP2.

8.2.2 Deformation/ Intrusions

The deformation measurements are the same as for Euro NCAP frontal test protocol [Euro NCAP 2009], which includes:

- Establishing a measurement reference on the rear of the vehicle
- The door reduction aperture at upper, waist and sill level,
- The rearward movement of the A-Pillar at waist and sill level (relative measure),
- The longitudinal, lateral and vertical movement of the centre of the top of the steering column
- Longitudinal and vertical movement of all the foot operated pedals.

In addition the following occupant compartment intrusion measurements should be taken (Dashboard, Footwell, Pedal axle)

Instrument Panel Top

1. Locate front lower corner of the side window in Z.
2. Locate outer edge of IP within height Z to Z+25mm and place target sticker.
3. Locate subsequent target stickers every 100mm (at height defined by 2.) inboard until the centreline of the vehicle (typically 6 stickers)

Note: Z is positive in the downwards direction

Instrument Panel Base (IPB)

4. Locate the highest point along the centreline of the seat squab and determine height in Z and distance from vehicle centreline
5. Locate target sticker in on nearest point on the IP in the same Z height and distance from vehicle centreline
6. Locate target stickers every 100mm inboard and outboard along the IP until the centre console and the outer edge of the IP is reached

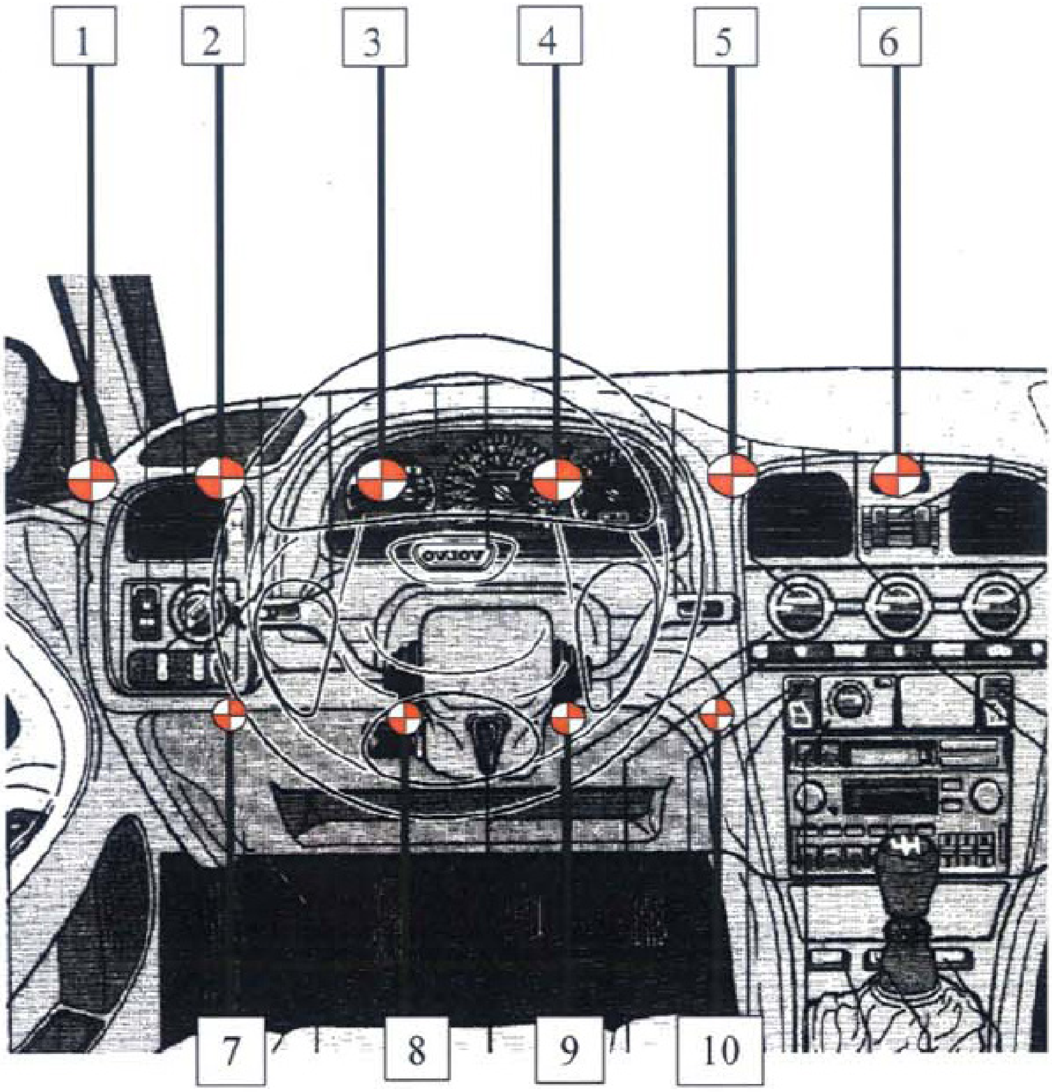

Figure 8.2: Measurement points at instrument panel.

Problems with IP Target Location

If significant deviation from the previous specification arises, then best judgement is needed and the criteria that need consideration are:

1. Try to locate target stickers on major components of the instrument panel – do not locate on the steering column surround as this will move independently of the majority of the IP.
2. At all times try to maintain the target stickers in the Z and X axis defined and only vary the Y axis by 100mm – if going below the instrument displays requires less deviation then proceeding around the top then place the target stickers in the former position.

Footwell Intrusion

1. Remove all carpet from the footwell requiring measurement.
2. Locate a target sticker behind the brake pedal in the same X and Z location as the brake pedal.

3. Place a pre-cut carpet with holes spaced at 100mm in the footwell and locate one of the pre-cut holes over the target sticker defined in 2. (Carpet can follow the contours of the footwell). If the pre-cut carpet is not available, use the 3D arm to position target stickers.
4. Locate additional target stickers in the location of the pre-cut holes. Only place stickers up to a maximum of 200 mm either side of the brake pedal. Place stickers up to a maximum of 200 mm (if possible) above and 300 mm below the point defined in 2.
5. If location tie up with local features on the footwell (such as drain holes) then move target stickers the minimum distance to clear such feature.

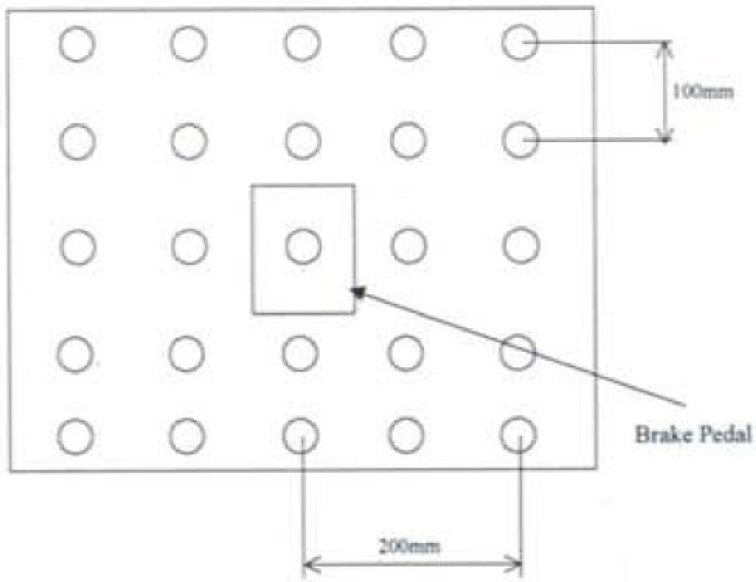

Figure 8.3: Footwell grid.

Pedal axis

1. Locate the outboard end of the clutch/brake pedal pivot axis.
2. Locate a target sticker at point defined by 1.

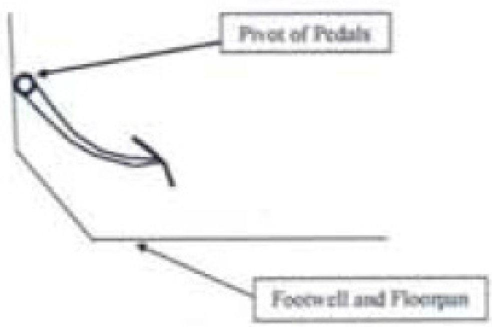

Figure 8.4: Pedal axis.

8.2.3 Force Measurements

If it is needed and if it is proven that the force measurement is accurate, an assessment could be introduced for the front end force.

A minimum frontal force level could be fixed as a first step in order to improve compartment strength for small cars and to ensure a minimum self protection level.

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FIMCAR
X – MDB Test Procedure: Test and Simulation Results

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

One of the test modes investigated during the FIMCAR project to improve frontal impact and compatibility is a so-called Moving Deformable Barrier test (MDB test). This is a frontal test with a moving test vehicle and moving trolley equipped with a deformable element. In various initiatives in Europe and the US this type of test is seen as a next step in the future evaluation of vehicle safety with a good possibility for harmonisation. Based on the experience of various projects prior to the FIMCAR project, a test protocol has been drafted in the FIMCAR project. Two main parameters: test speed and trolley mass, key factor to define the severity of the MDB tests, were defined during the FIMCAR program.

Using the draft protocol a number of MDB tests were carried out, the main objectives of the test were:

- Analysis of the feasibility of the test set up and protocol
- Definition of the test severity; trolley mas and impact speed
- Assessment of repeatability and reproducibility
- Development of compatibility metric / horizontal load spreading

The results of 15 MPDB test were used for the FIMCAR investigations. In general terms, the tests according to the draft protocol were feasible in various laboratories using different test trollies. Special attention is needed for the wheel alignment of trolley and test vehicles to avoid incorrect offsets.

For the explored vehicle mass range, kerb weight from 1000kg to 2200 kg, a fixed trolley mass of 1500 kg and a test speed of 50 km/h (for vehicle and trolley) results in an acceptable test severity. For vehicles outside this range, for example light electrical vehicles and heavy SUV's, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out to date. These series of tests both showed good results, giving an indication for good R&R, however, more tests are needed to make this statement statistically relevant.

Various investigations have been made for compatibility metrics to assess the load spreading of the tested vehicles. It was not possible to define metrics based on load cell wall recordings or trolley accelerations. The metric for horizontal load spreading based on the deformation of the PDB barrier is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm (Row 3 and Row 4 of the Full width Load Cell Wall) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicles with an even (homogeneous) deformation pattern or a barrier with localised holes.

The FIMCAR project proves that the MPDB test is a good candidate for future frontal compatibility test and assessment activities. More tests and studies are needed to define the test severity for light and heavy vehicles and to confirm the R&R results.

International discussions are needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in the shorter term, as it has advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of real life vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken so far. In addition another procedure (tests with a moving deformable barrier) is getting more and more into the focus of today's research programmes.

Within this project different off-set, full overlap and moving deformable barrier (MDB) test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages (WP). WP1 (Accident and Cost Benefit Analysis) and WP5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with actual car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

Within the previous deliverable (FIMCAR Deliverable D4.1) [Uittenbogaard 2013 / Section IX] a test procedure was drafted for MDB tests. Based on this test protocol, a series of 12 tests using the PDB as the deformable barrier were conducted by different project partners. The results of these tests, extended with results of 3 tests carried out outside the FIMCAR project and a supportive simulation study, are presented and analysed within this report. This report combines the two originally planned deliverables D4.2 and D4.3 as it appears to be better to combine the experience with the original test protocol and the final test protocol. Furthermore it turned out that the MPDB test protocol according to FIMCAR Deliverable D4.1 does not need any change for the time being.

1.3 Structure of this Deliverable

In Chapter 2 the general boundary conditions of the test series are explained. The different test houses, test vehicles as well as the test matrix are presented. In Chapter 3 the general results are presented not only for the baseline tests, but also for a number of variations in the test specifications. These results include vehicle as well as trolley accelerations, vehicle deformations and dummy readings. The results of the subsequent assessment methods are provided in Chapter 0. A limited investigation on repeatability and reproducibility is presented in Chapter 6. The report ends with a discussion of feasibility and test severity (7.1), compatibility metrics (7.2) and repeatability and reproducibility (7.3) in Chapter 7. Additionally, 1 appendix is added with details of the SUV 3 simulation results.

2 TEST AND SIMULATION PROGRAM

2.1 Test Protocol

As a first step the “Moving Deformable Barrier Test protocol”, a draft test protocol for this type of test was set up. This draft test protocol was submitted as FIMCAR deliverable D4.1 [Uittenbogaard 2013 / Section IX]. This test protocol is based on:

- MDB tests as developed and carried out by TNO in an internal R&D project [Versmissen 2006].
- Review of draft test protocols from different continents, evaluated with a European perspective for potential harmonisation.

As the development of a new deformable barrier was out of the scope of the FIMCAR project, the PDB barrier as used in WP2 “Offset test” was selected for the MDB test protocol. Therefore, the MDB tests conducted within this test program are further also addressed as MPDB tests. Two main test specifications could not be fixed in the original FIMCAR MDB test protocol. Too little test information, especially with various test velocities, was available prior to the FIMCAR project to define the optimal test severity. To define the severity during the FIMCAR project, the following parameters were used in the test program:

• Test speed	• 50 km/h - also tests with 45 and 56 km/h are carried out
• Trolley mass	• 1500 kg - also simulations with 1300 kg and 2200 kg respectively are carried out.

For all tests the applicable test speed and trolley mass are mentioned in the test description. All tests conducted within the FIMCAR project are carried out using the FIMCAR test protocol, with one exception. At some point in time during the FIMCAR project it was decided to install the Hybrid III 5th percentile female dummy instead of the Hybrid III 50th percentile male dummy on the front passenger seat. This decision for all FIMCAR test types was taken, to also investigate the protection level of a, so far, neglected group of occupants that still suffer a significant amount of injuries in real life crashes. As a number of MPDB tests were already carried out prior to this decision, both dummies - 50th male and 5th female - are found on the passenger seat in the MPDB test program presented within this report.

2.2 Test Laboratories

During the FIMCAR project MPDB tests were carried out in several different laboratories (see Table 1). For the MDB test, a special test trolley is required. Table 1, also specifies, besides the number of conducted tests, which trolley was used at the respective laboratory.

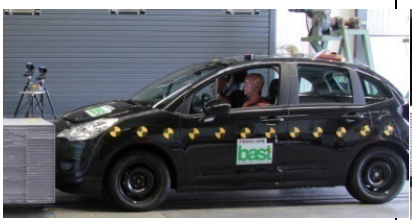
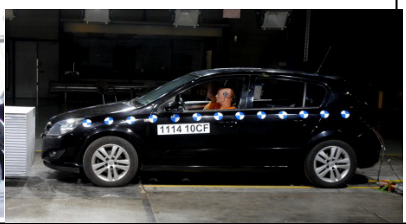
Table 1: FIMCAR MDB Test laboratories.

Laboratory	Number of tests	MDB Trolley
BAST	1	TNO/TTAI trolley
	1	New build trolley, according to TNO specifications
FIAT	1	TNO/TTAI trolley
IDIADA	2	Modified ECE R95 trolley
Renault	1	TNO/TTAI trolley
UTAC	1	Modified ECE R95 trolley
TNO/TTAI	4	TNO/TTAI trolley: Special MDB trolley as developed and build in an internal TNO project

2.3 Test Vehicles

During the FIMCAR program MDB tests with the following vehicles were carried out:

Table 2: FIMCAR MPDB test vehicles.

Supermini		
		
Supermini 2	Supermini 3	Citycar 1
Supermini	**Small family car**	
		
Supermini 1	Small Family Car 2	
SUV / Off road		
		
SUV 4	SUV 2	SUV 1

The vehicles were selected by the consortium, using the following criteria:

- Coverage of the required mass range (kerb weight 1000 kg to 2200 kg)
- Availability of additional (crash) test and/or simulation results e.g. from Euro NCAP
- Access through FIMCAR partners
- Different compatibility design and expected results
- Focus on light and heavy vehicles as they are critical for the definition of a proper test severity

2.4 Test Matrix

The main specifications of the FIMCAR tests are presented in Table 3.

Table 3: FIMCAR test matrix.

Vehicle	Laboratory	Velocity [km/h]	Trolley mass [kg]	Remark
Supermini 2	Fiat	50	1500	Baseline test
Citycar 1	TTAI	45	1500	Effect velocity
Citycar 1	TTAI	50	1500	Baseline test
Supermini 3	TTAI	45	1500	Effect velocity
Supermini 3	TTAI	50	1500	Baseline test
Supermini 1	BAST	50	1500	Baseline test
Small Family Car 2	BAST	56	1500	Effect velocity
Small Family Car 2	IDIADA	50	1500	Baseline test Reproducibility (TTAI)
Small Family Car 2	TTAI	50	1500	Baseline test Reproducibility (IDIADA)
SUV 1	IDIADA	50	1500	Baseline test
SUV 2	UTAC	50	1500	Baseline test
SUV 4	TTAI	50	1500	Baseline test

Additional to the FIMCAR tests, the results of a number of moving progressive deformable barrier (MPDB) tests carried out by TNO, are used in this deliverable, namely:

- Two tests with Small Family Car 2, part of an internal TNO development program
- One test with a Supermini 2, sponsored by the Dutch RDW, for GRSP activities.

The main specifications of these tests are presented in Table 4.

Table 4: Additional MPDB tests.

Vehicle	Laboratory	Velocity [km/h]	Trolley mass [kg]	Remark
Supermini 2	TNO	56	1500	GRSP information
Small Family Car 2	TNO	45	1500	MPDB development Repeatability
Small Family Car 2	TNO	45	1500	MPDB development Repeatability

2.5 Simulation Matrix

To study the effect of trolley mass and test velocity, VCC has carried out a simulation study using a numerical model of SUV 4 and the PDB computer model as developed by Opel as part of the FIMCAR project. The simulation matrix with the main parameter variations is presented in Figure 2.1.

	Simulation	Barrier	Car velocity [kph]	Barrier velocity [kph]	Relative velocity [kph]	Barrier mass [kg]	Car mass [kg]	Initial kinetic energy [kJ]
Baseline	SUV 4	MPDB	50	50	100	1500		376
	SUV 4	MPDB	50	50	100	1300		357
	SUV 4	MPDB	50	50	100	2200		444
	SUV 4	MPDB	56	56	112	1500	2400	472
Euro-NCAP	SUV 4	ODB	64		64			379
R94	SUV 4	ODB	56		56			290
Fixed PDB	SUV 4	PDB	60		60			333

Figure 2.1: Simulation matrix / SUV 4 simulations.

3 TEST RESULTS

3.1 General Information

Only the main results needed for the definition of the test severity and development of the test protocol are presented in this deliverable.

An overview of the main test characteristics is presented in Table 5.

Table 5: Main test characteristics.

Lab	Number	Vehicle	Vehicle mass [kg]	Trolley mass [kg]	Vehicle speed [km/h]	Trolley speed [km/h]	Offset [%]	Driver	Passenger
Reference tests: Velocity 50 km/h / Trolley mass 1500 kg / Offset 50%									
TTAI	F114204	Supermini 3	1136	1503	50.4	50.4	50	50th	5th
TTAI	F112902	Citycar 1	1159	1503	50.1	50.1	50	50th	5th
Fiat	17204A	Supermini 2	1225	1512	50	50	50	50th	50th
BAST	FM06C3MB	Supermini 1	1301	1500	50.1	50.1	50	50th	5th
IDIADA	111410CF	Small Family Car 2	1482	1500	50.4	50.1	50	50th	5th
TTAI	F103904	Small Family Car 2	1484	1512	49.8	49.4	50	50th	50th
IDIADA	122701CF	SUV 1	1907	1500	50.4	50.4	51	50th	50th
UTAC	AFFSEP1202056	SUV 2	1912	1500	50.5	50.5	50	50th	50th
TTAI	F105005	SUV 4	2440	1510	49.8	49.4	50	50th	5th
Low speed tests: Velocity 45 km/h / Trolley mass 1500 kg / Offset 50%									
TTAI	F114303	Supermini 3	1136	1503	44.7	44.8	50	50th	5th
TTAI	F114203	Citycar 1	1156	1503	45.1	44.9	55	50th	5th
TNO	F054801	Small Family Car 2	1403	1500	45.1	45.1	50	50th	50th
TNO	F055001	Small Family Car 2	1405	1500	45.2	45.1	50	50th	50th
High speed tests: Velocity 56 km/h / Trolley mass 1500 kg / Offset 50%									
TNO	F084003	Supermini 2	1161	1514	56.1	55.8	50	50th	50th
BAST	FM01OPMB	Small Family Car 2	1446	1533	56	56	56	50th	50th

Remarks:

- All tests are carried out within the tolerances as specified in the test protocol [Uittenbogaard 2013 / Section IX], with three exceptions :
  - Small Family Car 2 high speed test by BAST : offset 56 instead of 50%
  - Citycar 1 low speed test by TTAI : offset 55 instead of 50%
  - SUV 1 baseline test by IDIADA: offset 51 instead of 50%
- The increased offset of these tests is taken into account during the test analysis.

3.2 Vehicle and Trolley Acceleration Results

3.2.1 Baseline Tests

For all vehicles, a baseline test has been carried out with the baseline specifications of a trolley mass of 1500 kg and a speed of 50 km/h. The resulting B-Pillar accelerations on the struck side are presented in Figure 3.1.

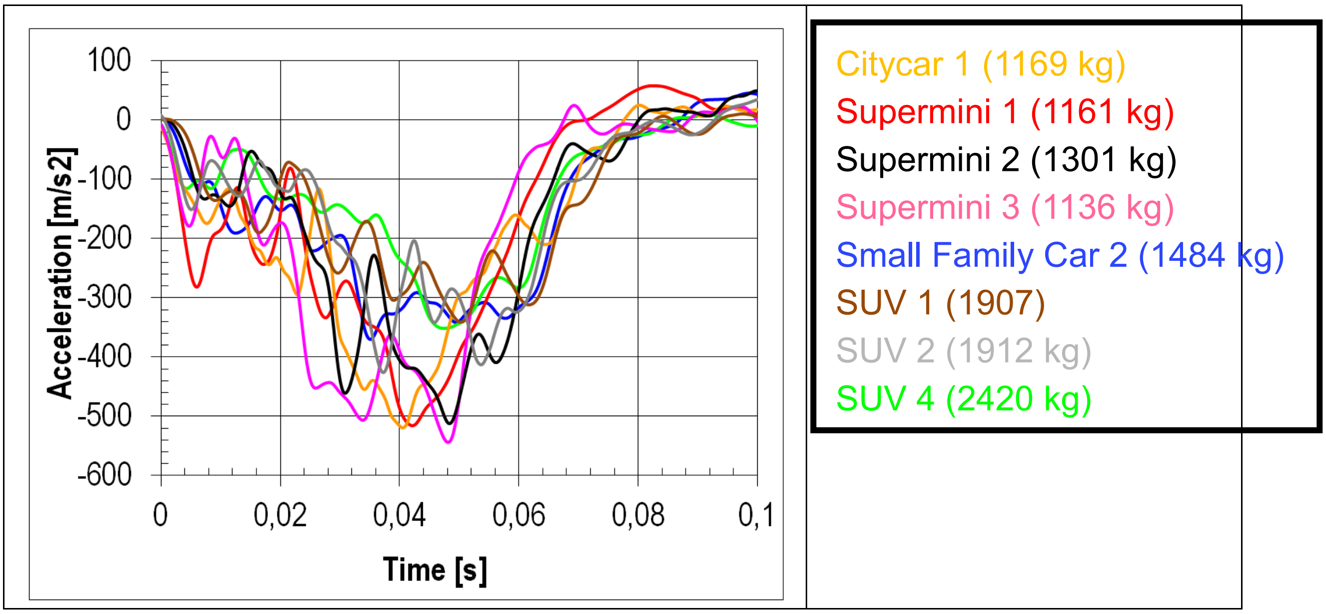


Figure 3.1: B-pillar acceleration / baseline tests.

The acceleration range is in some cases slightly higher or else in line with the results of current Euro NCAP tests such as those plotted by Hynd et al. [Hynd 2010]. Their study shows average Euro NCAP peak accelerations of 30 g. It is clear that the acceleration is mass dependent as light vehicles are pushed back by the trolley and heavy vehicles pushed the trolley backward resulting in higher and lower accelerations, respectively. This is in line with car-to-car impacts between vehicles with different masses. The duration of the pulses is significant shorter than the results of UN-ECE Regulation 94 or Euro NCAP tests, as trolley and vehicle are both moving.

3.2.2 Small Family Car 2 Tests

To study the effect of the impact velocity, additional tests were carried out with Small Family Car 2 - a car with an average mass for the European fleet. For these tests, the trolley mass was kept at 1500 kg and the impact velocity was varied as follows:

- low speed: 45 km/h,
- baseline speed: 50 km/h / two reproducibility tests
- high speed: 56 km/h

The resulting accelerations of the vehicle B-pillar as well as of the trolley are presented in Figure 3.2.

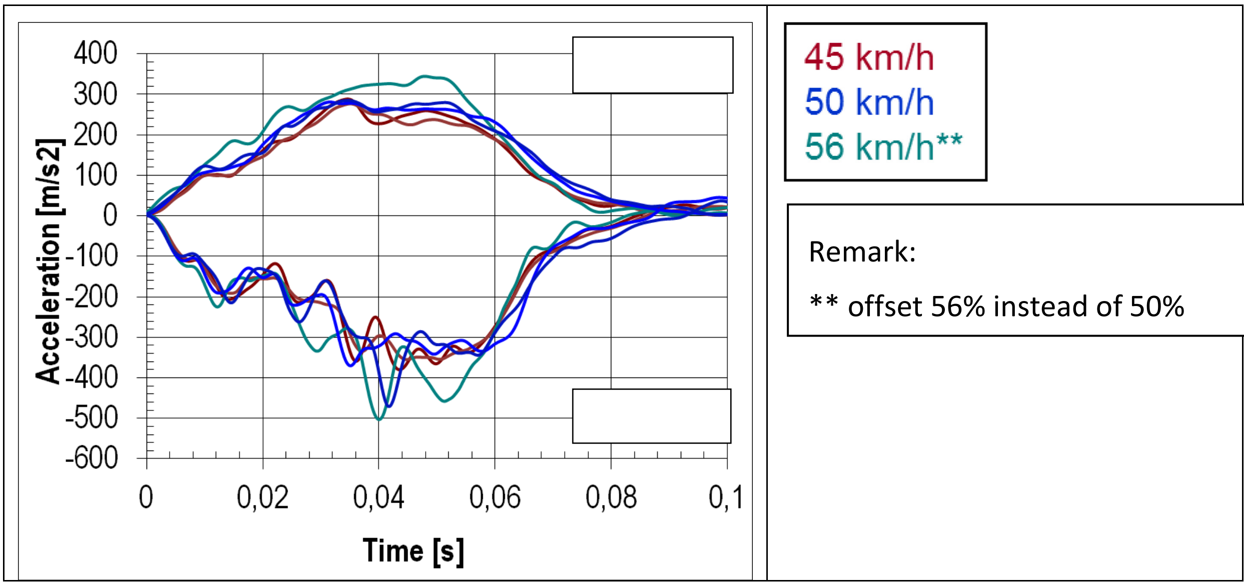


Figure 3.2: B-pillar and trolley acceleration / Small Family Car 2 tests.

Both 50 km/h tests show a good reproducibility. The trolley and vehicle accelerations of the 56 km/h test are significantly higher than the results of the other test. This is mainly caused by the higher offset of 56% instead of 50%.

3.2.3 Citycar 1 Tests

The Citycar 1, a light vehicle, has been tested with a trolley mass of 1500 kg and two impact velocities: 45 km/h and 50 km/h. The accelerations of the vehicle B-pillar and of the trolley are presented in Figure 3.3.

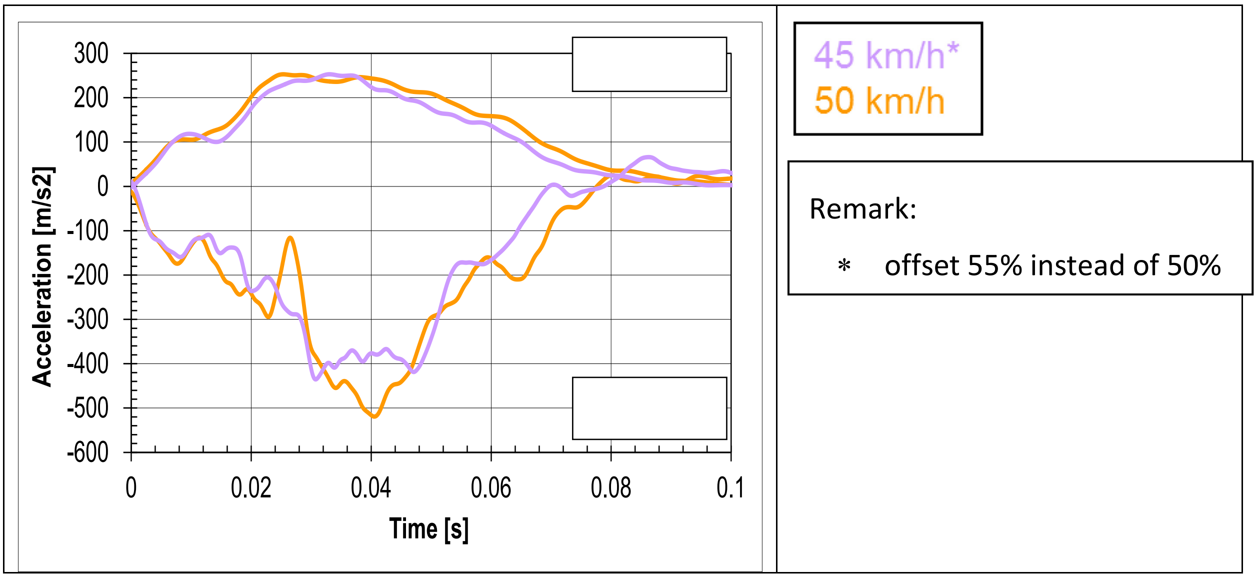


Figure 3.3: B-pillar and trolley acceleration / Citycar 1 tests.

The acceleration of trolley and vehicle are significant higher in the 50 km/h test though the offset in the low speed test is higher, 55% instead of 50%.

3.2.4 Supermini 3 Tests

The Supermini 3, also a light vehicle, has been tested with a trolley mass of 1500 kg and two impact velocities: low 45 km/h and baseline 50 km/h. The accelerations of the vehicle B-pillar and trolley are presented in Figure 3.4

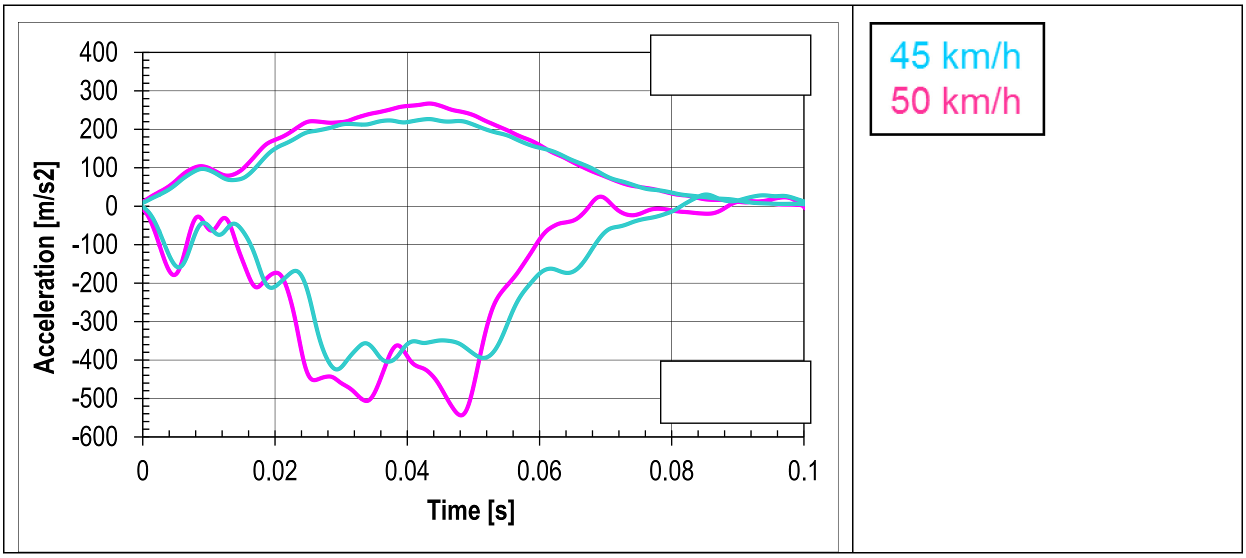


Figure 3.4: B-pillar and trolley acceleration / Supermini 3 tests.

The difference between the accelerations is larger compared to the Citycar 1 tests, as both test are carried out with the correct offset.

3.2.5 Supermini 2 Tests

The Supermini 2, another light vehicle, was tested with a trolley mass of 1500 kg and two impact velocities: 50 km/h and 56 km/h. The accelerations of the vehicle B-pillar and of the trolley are presented in Figure 3.5.

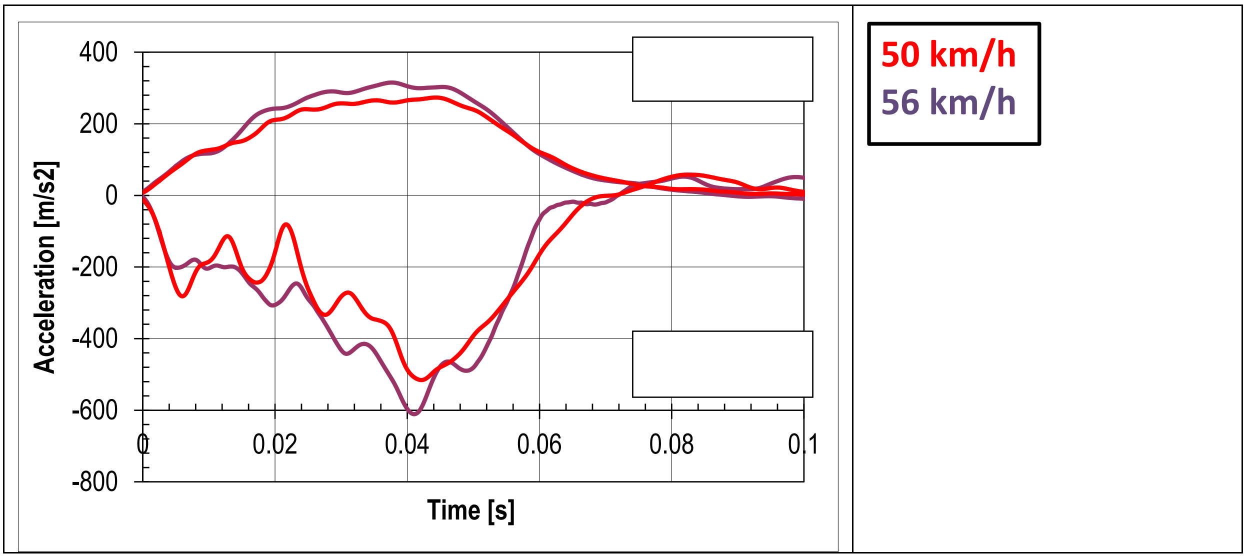


Figure 3.5: B-pillar and trolley acceleration / Supermini 2 tests.

The difference between the accelerations is greater than in the Citycar 1 tests, as both tests are carried out with the correct offset and comparable to the Supermini 3 tests.

3.2.6 Mean B-pillar Acceleration and Delta-v.

To compare all the results of all vehicles, the maximum mean B-pillar acceleration of the MPDB tests are presented in Figure 3.6 and Figure 3.7. The maximum mean acceleration has been defined as:

$$\max mean\ acc = \frac{\max Delta - v}{time\ to \max Delta - v}$$

For the Supermini 3, Citycar 1, Supermini 2, Small Family Car 2 and SUV 4 also the results of other test modes, if available, are presented. For the tests carried out in the final phase of the FIMCAR project, SUV 1, Supermini 1 and SUV 2 no reference results are available. It is clear that, in general, lower B-pillar accelerations are measured in heavier vehicles. However for all vehicles with a reference test, the MPDB B-pillar acceleration is higher than in Euro NCAP tests. For the Small Family Car 2 and SUV 4, the MPDB is more severe than the fixed offset test.

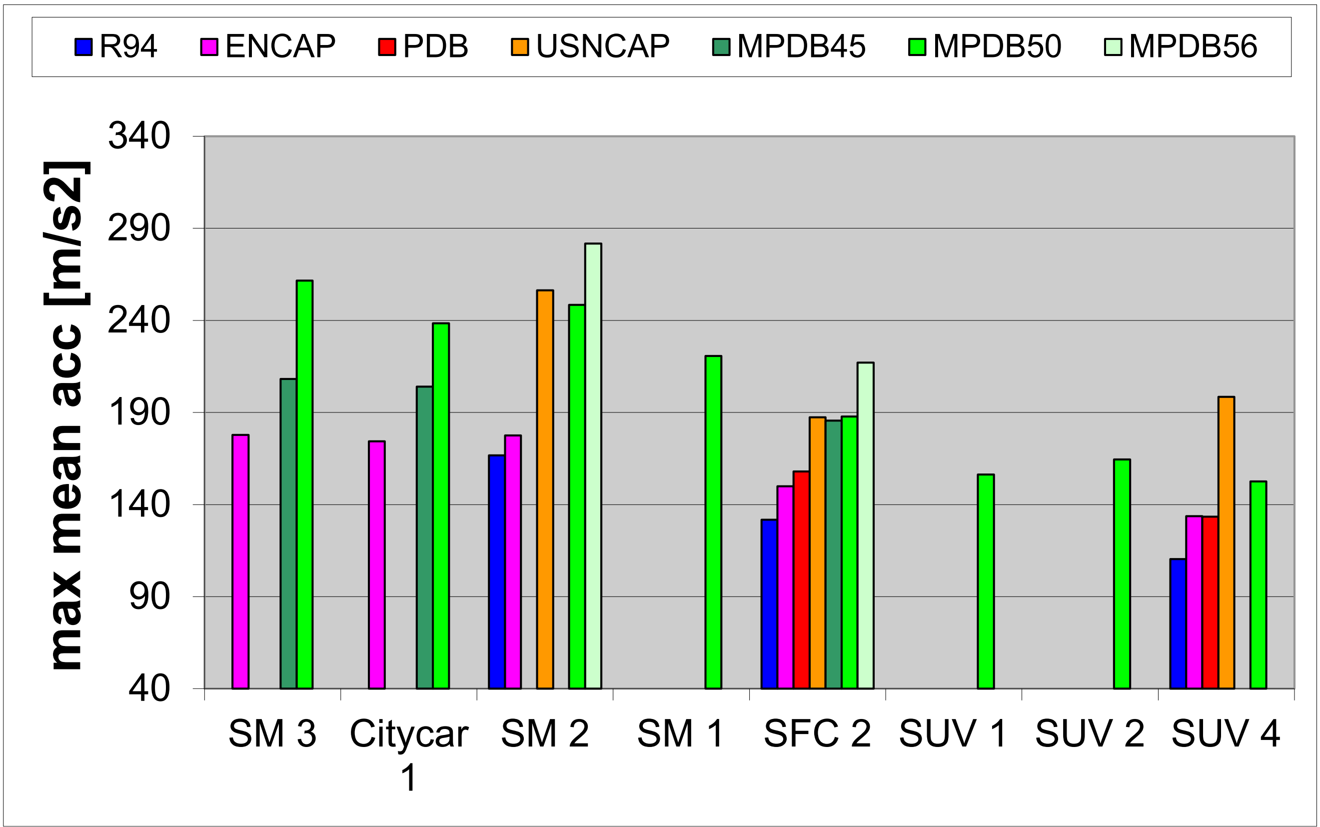


Figure 3.6: Maximum mean B-pillar accelerations.

The velocity changes of the MPDB tests and available reference tests are presented in Figure 3.7. Again for some vehicles the results of reference tests are presented. Due to the test mode, both trolley and vehicle moving, the delta-v of the MPDB is depending on the mass of the tested vehicle. For static tests the delta-v is always higher than the test speed due to the vehicle rebound.

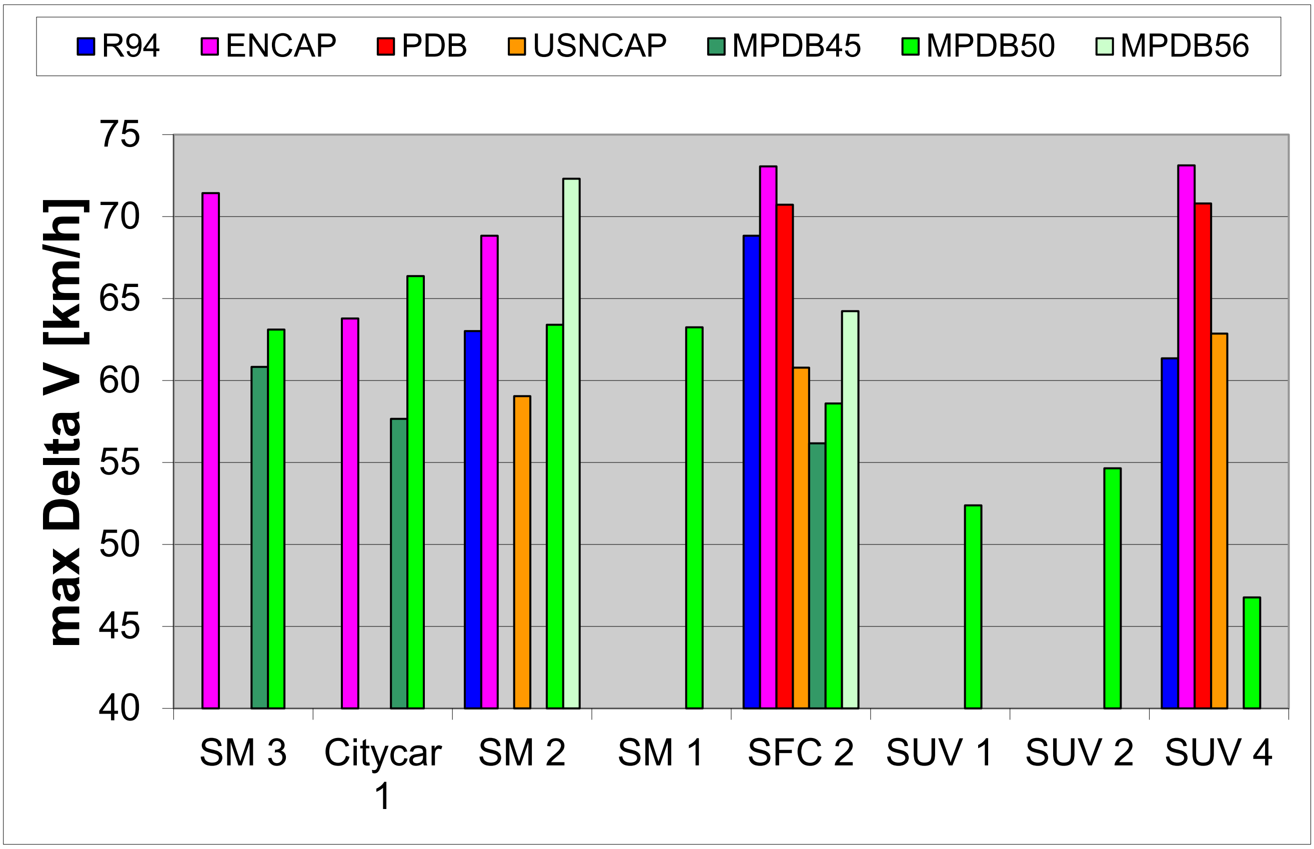


Figure 3.7: *MPDB tests / delta-v results*.

3.3 Vehicle Deformations

After all the MPDB tests, a number of static measurements have been carried out to record vehicle deformations. To compare the MPDB static measurements, the static measurements as specified in the Euro NCAP frontal test protocol measurements were also used. The most relevant measurement to specify for the compartment strength is the displacement of the A-pillar. These results are presented together with the results of available reference tests in Figure 3.8.

It can be seen that for the small, as well as the average sized vehicles, the A-Pillar deformations are significantly higher in the baseline MPDB test compared to the reference test. This test mode is more severe for the compartment strength than UN-ECE Regulation 94 and Euro NCAP. However even with this more severe test mode all values except the ones from the MPDB50 test with the Citycar 1 are below the proposed maximum A-pillar displacement of 50 mm.

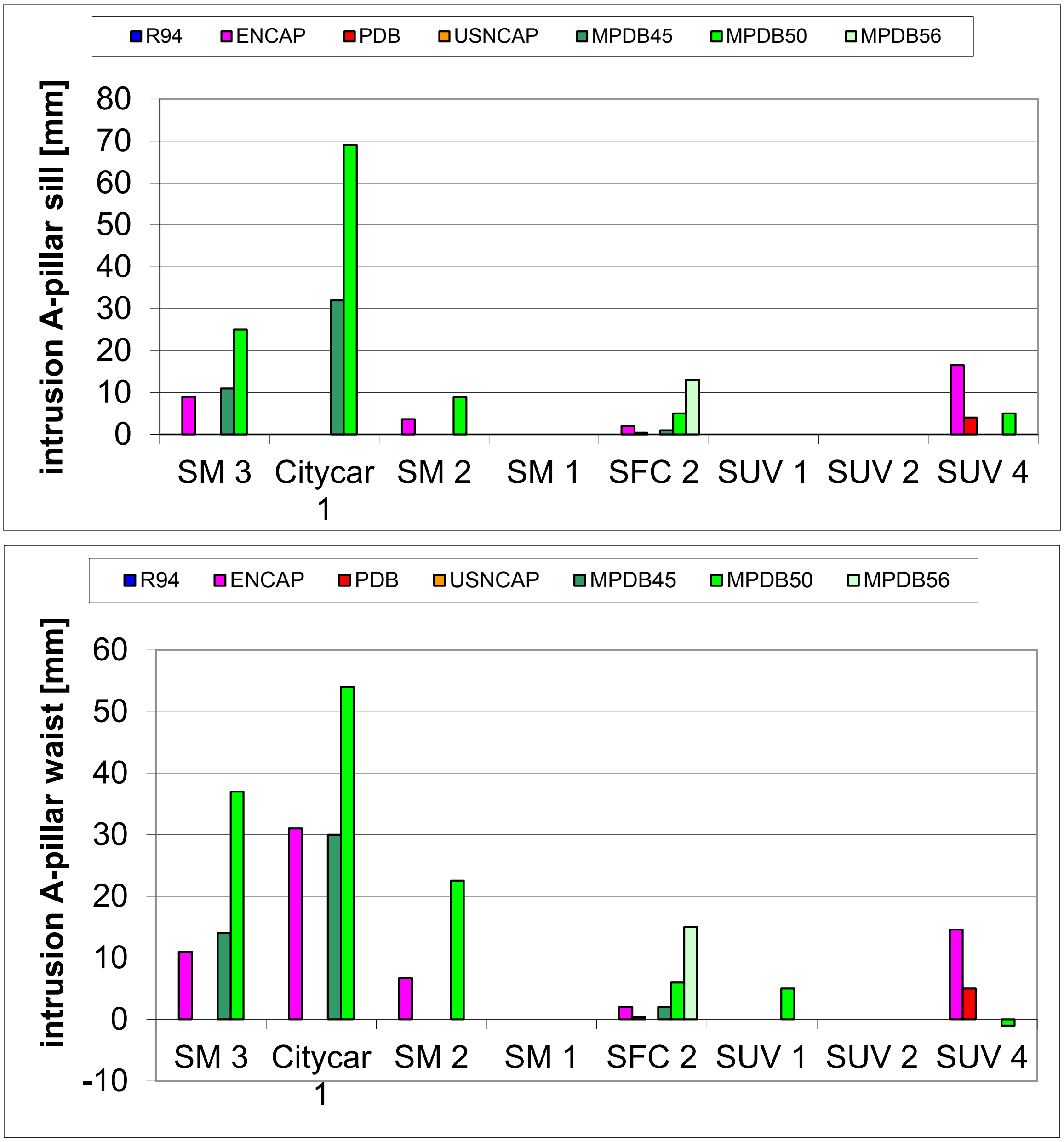


Figure 3.8: Deformation results of the A-pillar at sill and waist level.

3.4 Dummy Results

3.4.1 General

Anthropometric test devices (ATDs), namely Hybrid III impact dummies, were installed in all test vehicles for the tests to give an indication on occupant injury risk during impact. However the sustainable injury risk is not only influenced by the chosen test mode, but also by the configuration of the occupant restraint system, which will be “filtering” a part of the test mode effects. It also needs to be taken into account that the restraint systems are not yet designed/optimised for the MPDB test mode, hence better dummy results are expected in the future when this test may be a part of the vehicle development process. One important issue influencing the effectiveness of the restraint system is its trigger time. As an indication, the airbag trigger time (which is also available for most of the reference tests) was recorded during the MPDB tests - the results are presented in Figure 3.9. In general, during the MPDB tests, the airbags are triggered earlier than in PDB or Euro NCAP tests.

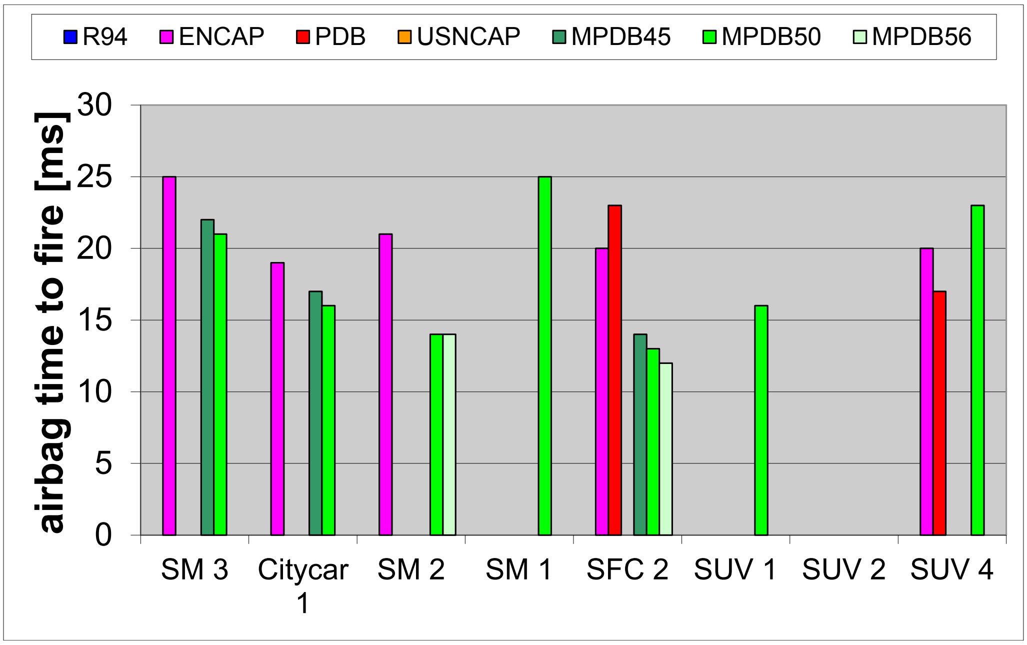


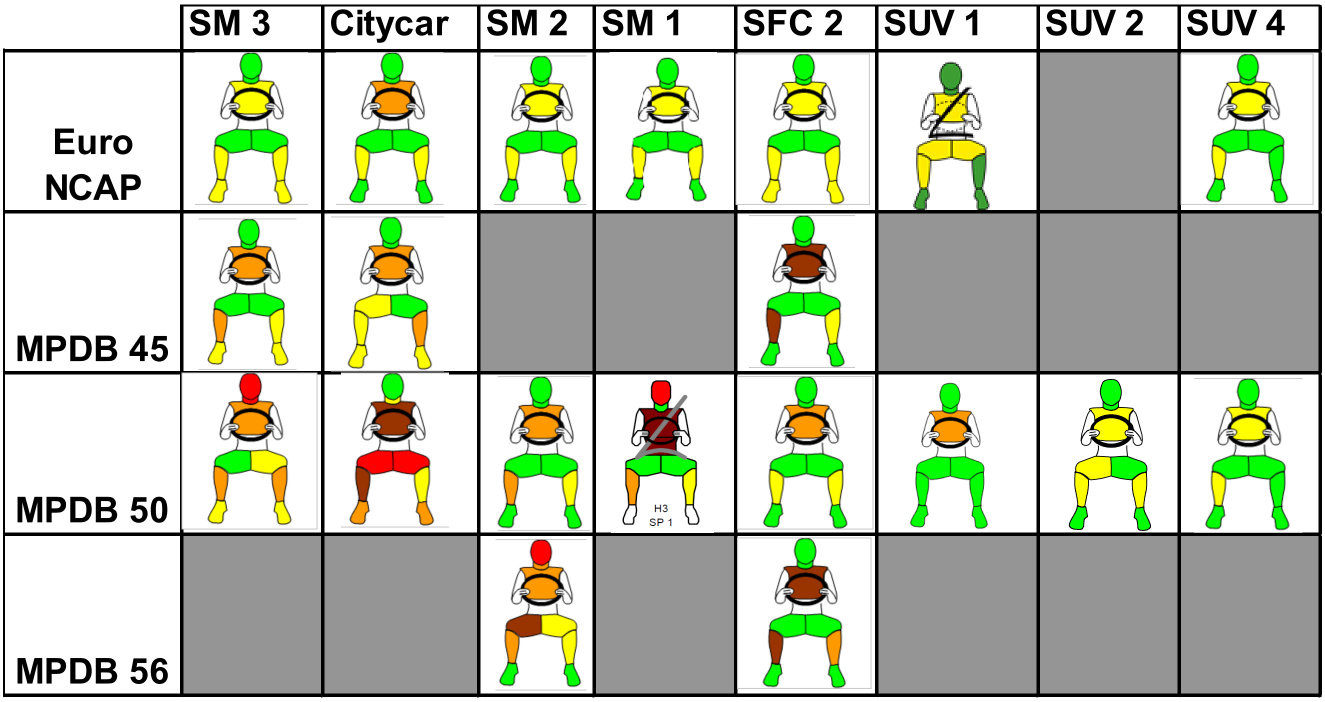
Figure 3.9: MPDB tests / airbag time to fire.

3.4.2 Dummy Results in Euro NCAP Lay Out

Due to the filtering effect of the restraint systems and the variations in airbag firing time, the dummy results are only an indication for the test severity. The total results for the driver presented in Figure 3.10 are prepared in the well-known Euro NCAP colour lay-out including obtained points as calculated based on the Euro NCAP ODB assessment procedure without modifiers. Only the driver's results are presented as in this position in all tests a Hybrid III 50th dummy was installed, so a comparison of the results was possible. The dummy results of light vehicles are worse than the corresponding Euro NCAP scores, the heavier vehicles scores are comparable with Euro NCAP scores.

Remark:

For the SUV 1 the total number of points is comparable although the loads to the different body regions are different. The most probable cause is that leg risks are mainly a result of intrusion and chest risks are mainly a result of car acceleration it appears that there is an higher acceleration in the MPDB but less intrusion.



	SM 3	Citycar	SM 2	SM 1	SFC 2	SUV 1	SUV 2	SUV 4
Euro NCAP	15.1	13.3	15.1	14.38	14.9	13.1		14.8
MPDB 45	11.9	11.4*			9.3			
MPDB 50	6.1	4.6	9.5	0 (capped)	12.7	13.9	13.8	14.9
MPDB 56			4		9.2**			

Figure 3.10: Injury risk indication based on Euro NCAP ODB assessment procedures.

3.4.3 HIC Results

For a number of the tests, a Hybrid III 5th percentile female dummy was installed on the co-driver seat, for these dummies no Euro NCAP scores are available. Therefore HIC values are presented in absolute values for all dummies installed in the MPDB tests, see Figure 3.11 and Figure 3.12.

For most MPDB50 and MPDB45 tests, HIC values are below the R94 requirements of 1000. The HIC values for the drivers in the Supermini 1 and the Supermini 3 MPDB50 tests are above this limit.

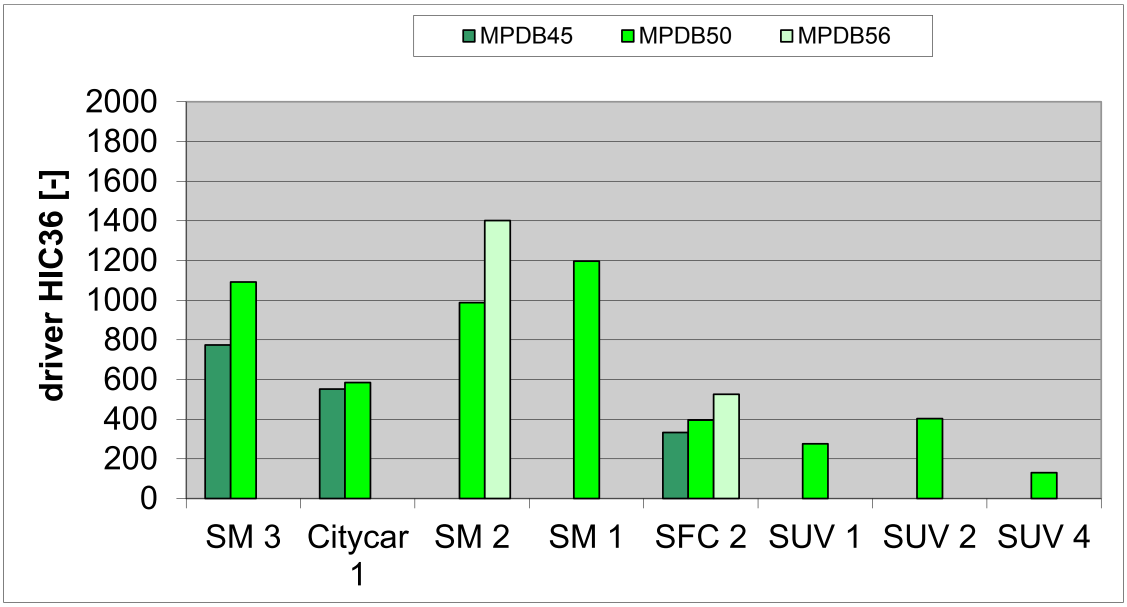


Figure 3.11: HIC results / driver.

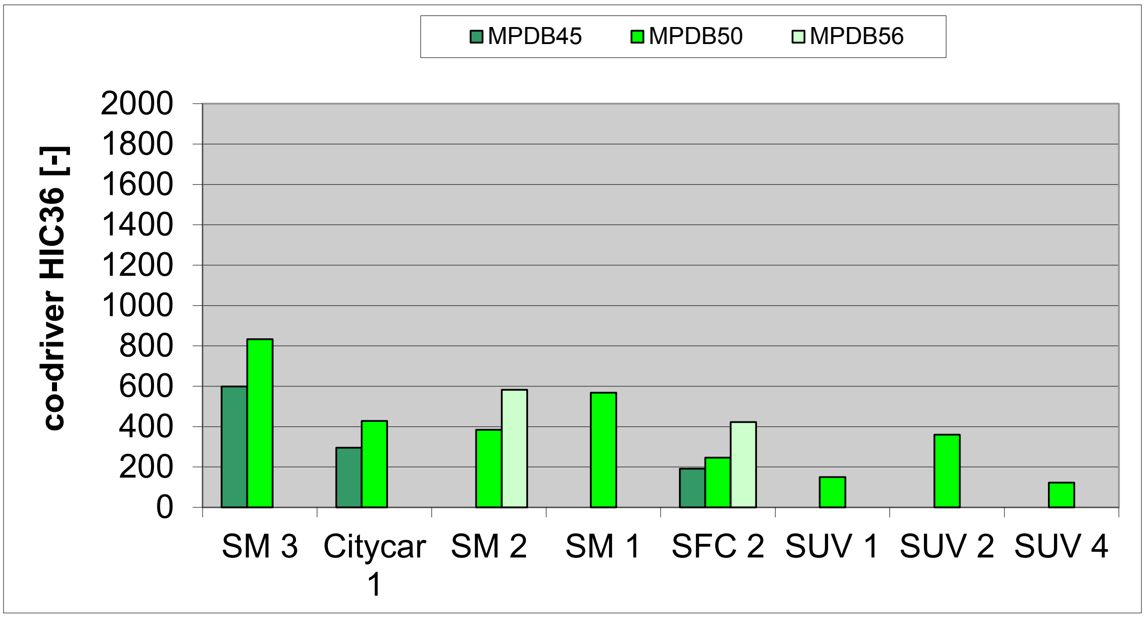


Figure 3.12: HIC results / co driver.

3.5 PDB Deformations

The PDB deformation, which forms the basis for a potential compatibility metric, is one of the main results of the tests. Pictures of the deformed barriers and a view of the scanned results are presented in Table 6 and Table 7, respectively.

Table 6: Barrier deformation results.

	45 km/h	50 km/h	56/km/h
Supermini 2			Not available
Citycar 1			
Supermini 3			
Supermini 1			
Small Family Car 2			
SUV 1			

Table 6: Barrier deformation results. *(continued)*

	45 km/h	50 km/h	56/km/h
SUV 2			
	45 km/h	50 km/h	56/km/h
SUV 4			

Table 7: PDB barrier scan results.

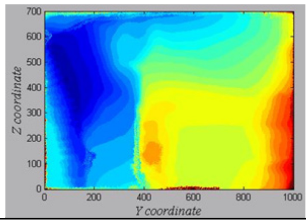
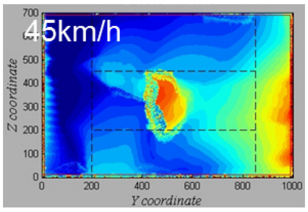
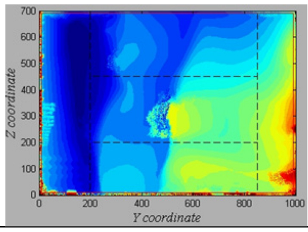
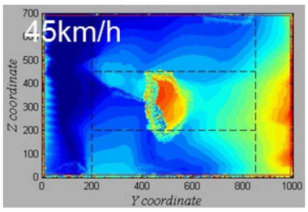
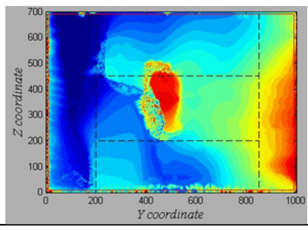
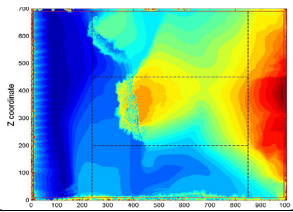
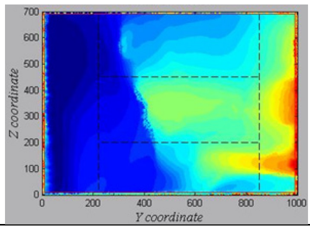
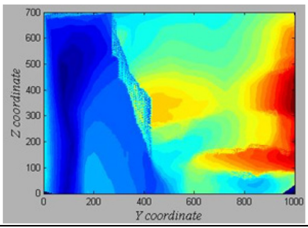
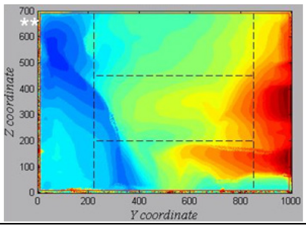
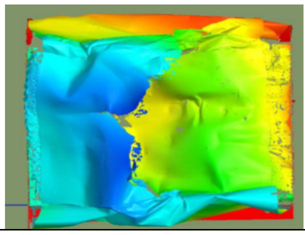
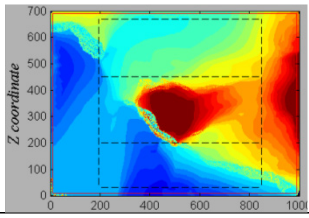
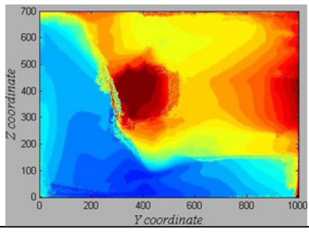
	45 km/h	50 km/h	56/km/h
Supermini 2			Not available
Citycar 1			
Supermini 3			
Supermini 1			

Table 7: PDB barrier scan results. (continued)

	45 km/h	50 km/h	56/km/h
Small Family Car 2			
SUV 1			
SUV 2	45 km/h	50 km/h	56/km/h
			
SUV 4			

4 SIMULATION RESULTS

The SUV 4 simulation results conducted by VCC are presented in detail in Section 0 “ A: SUV 4 simulation results” of this report.

The B-pillar acceleration results of these simulations are presented in Figure 4.1. These results show the same trend as the MPDB test results.

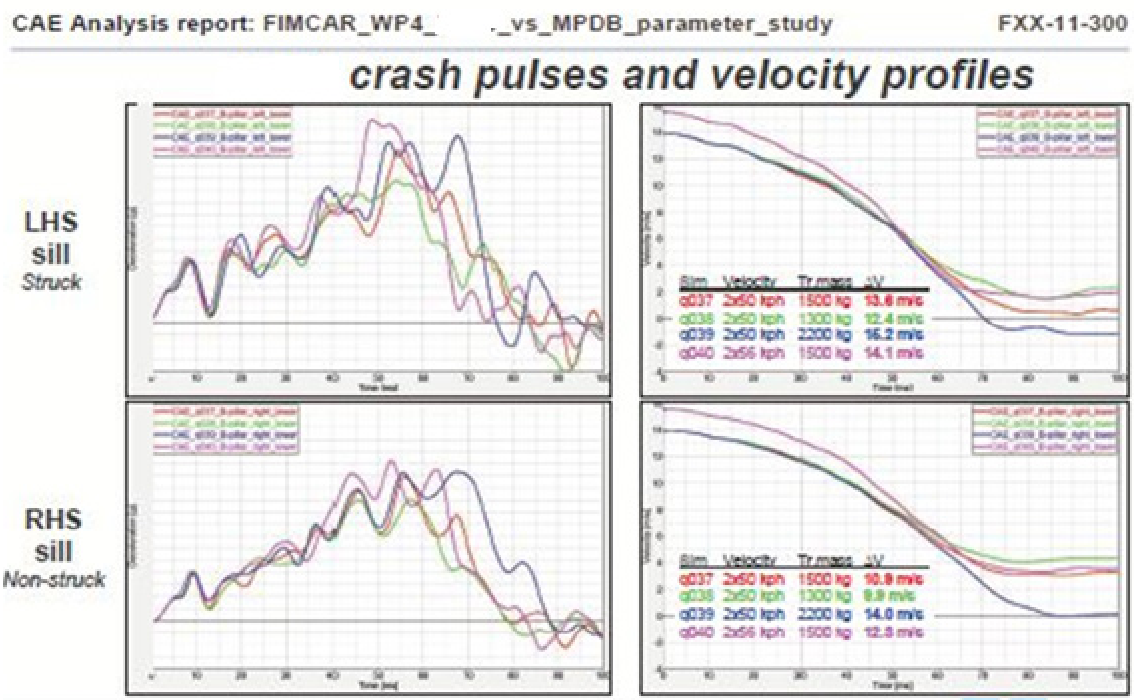


Figure 4.1: VCC Simulations / B-pillar accelerations.

The normalised compartment displacement results are presented in Figure 4.2. All MPDB simulations result in lower compartment displacements as the Euro NCAP tests but higher than the ECE R94 test. The MPDB simulations with 1500 kg trolley mass and 50 km/h test speed is closest to the PDB offset test results.

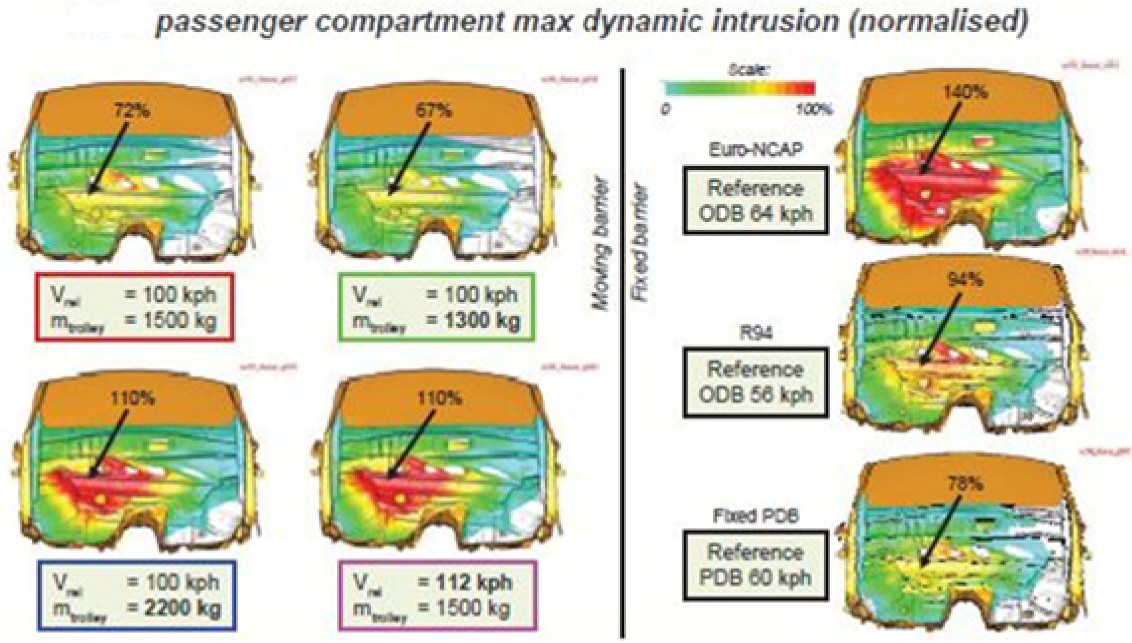


Figure 4.2: VCC Simulations / Normalized compartment displacement.

5 ASSESSMENT RESULTS

5.1 PDB Deformations

The deformation of the PDB barrier was considered for a long time as a potential basis for a metric to assess the compatibility of vehicles. Especially the FIMCAR priority number 1 topic “horizontal load spreading” should be assessed by the PDB barrier deformation. Various potential metrics were developed within the FIMCAR project. As the evaluation of these metrics is one of the main activities addressed by WP2 “Offset tests” which is based on the PDB offset tests, these metrics are described in [Lazaro 2013 / Section V].

To develop the matrix test and simulation data from vehicle impacts with the PDB or MPDB were collected for different vehicle models spanning a range of vehicle masses and vehicle classes. The main information analysed was the deformation pattern of the PDB barrier after a test result. These deformation plots were reviewed and subjectively assessed by the experts. The subjective assessments were used to develop key characteristics that should be detected by a numerical assessment of the 3D data. These subjective assessments were then compared to different objective (numerical) assessments for the barriers to ensure correlation of the results and then validated with available car-to-car data. Assessment of the influence of assessment area and scanning resolution was also performed.

The deformation profiles could be grouped into three main groups where the horizontal and vertical load spreading distinguished vehicles with good or poor performance. The main focus was the development of an assessment of the horizontal load spreading between the longitudinals. A metric based on the slope, or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm (Row 3 and Row 4 of the Full width Load Cell Wall) was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 (higher results are worse than lower ones) could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

The MPDB assessment results of this most promising metric are presented in Figure 5.1.

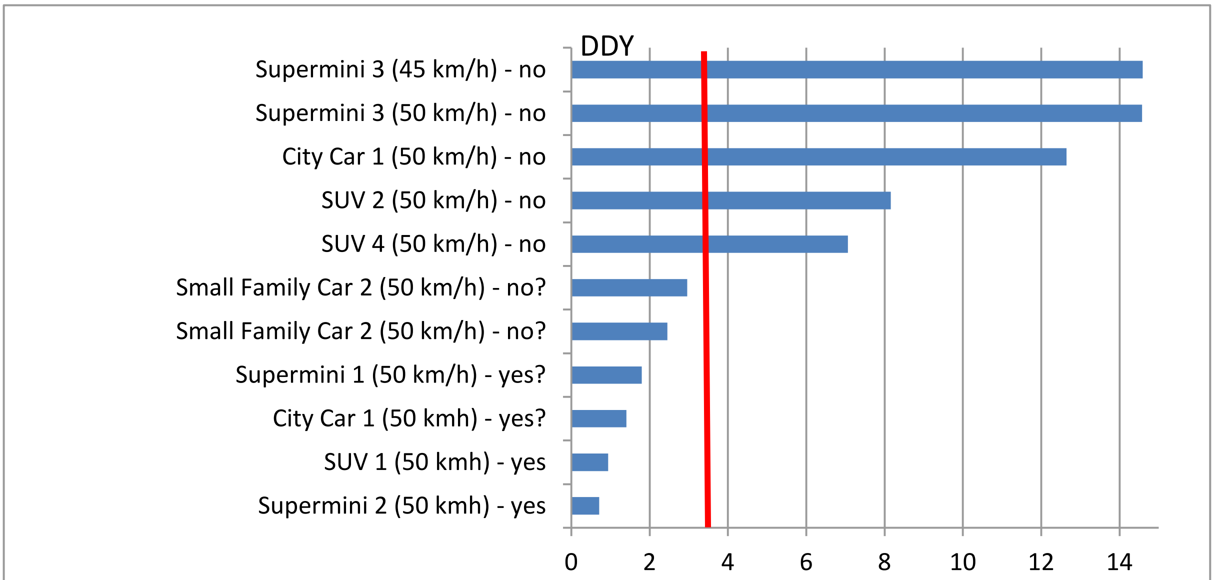


Figure 5.1: MPDB assessment results.

The basic idea of this metric is that a good horizontal load spreading will not cause strong local deformation in form of holes within the assessment zone. The remarks “yes(?) / no(?)” refer to whether or not a good spreading of the load was obtained during the test based on the judgment of an expert of the PDB deformation. The results presented in Figure 5.1 show a good correlation between the expert view during the development phase and DDY 99th% values. The question marks referred to situations where the expert has no clear view about the required results. For the metrics these unclear observations are located between real “yes” and “no” observations. The red line shows the proposed target value of 3.5 based on the PDB results analysis.

5.2 Trolley Acceleration

Investigations were carried out to establish if the trolley acceleration, a recording independent of the vehicle, could be used for compatibility assessment. In Figure 5.2 the PDB deformations, ranked from good to poor compatibility according to an expert are presented with the related trolley acceleration and force. The hypotheses that good compatibility will result in a smooth trolley acceleration, see ranking, could not be confirmed. The results of MPDB tests carried out as part of a development project by TNO were used for this analysis. Based on these negative results it was decided not to repeat this analysis for the FIMCAR tests.

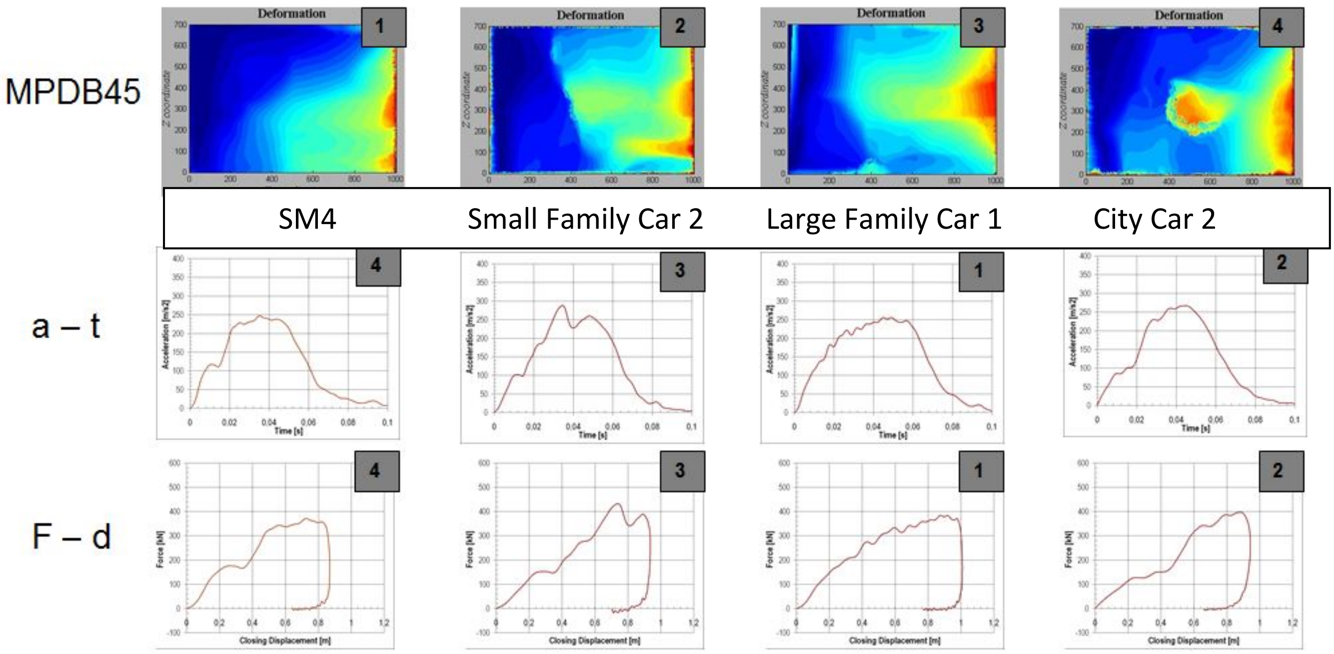


Figure 5.2: PDB deformation / trolley acceleration [Versmissen 2006].

5.3 Load Cell Wall (LCW) Recordings

The TNO/TTAI trolley is equipped with a lightweight Load Cell Wall that has identical load cell dimensions (125 x 125 mm) as the Load Cell Wall used in the full width tests. The main goal of including this load cell barrier is to use the additional information for vehicle development activities. For vehicle assessment purposes the load spreading between the load cells which is highly influenced by the PDB barrier itself is not found sufficiently robust. The use of load cells was already investigated by UTAC during the PDB development activities and was not found to be suitable for this kind of testing [Delannoy 2003].

In Figure 5.3 the load cell wall forces from the Small Family Car 2 and SUV 4 test at the moment of maximum force are presented. Comparing PDB barrier deformations with the recorded loads show that the recorded loads are present in a much bigger area than the local deformations shown in the PDB deformation.

Only the results of MPDB tests carried out as part of a development project by TNO were used for this analysis. Based on these negative results it was decided not to repeat this analysis for the FIMCAR tests.

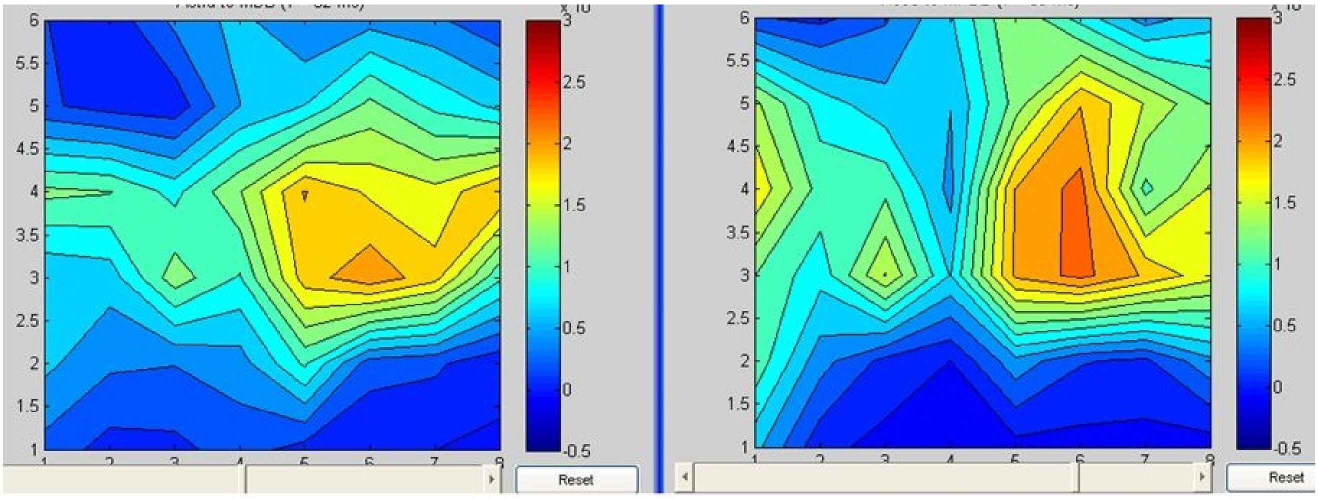


Figure 5.3: Maximum load cell forces MPDB test: Small Family Car 2.

To check the quality of the load cell measurements the total forces were compared by the force calculation based on trolley mass multiplied with the trolley acceleration.

In Figure 5.4 the acceleration of the Small Family Car 2 and SUV 4 MPDB test are presented. The acceleration calculated from the total force measured by the Load Cell Wall shows good correlation with the recorded acceleration.

Small Family Car 2 to MDB

SUV 4 to MDB

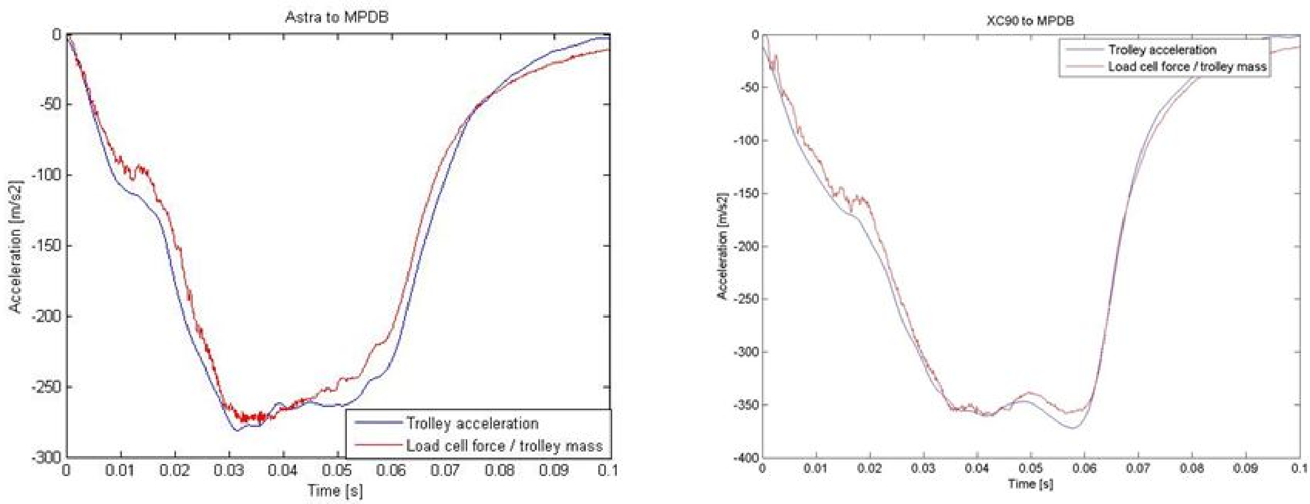


Figure 5.4: Total force results / Small Family Car 2 and SUV 4.

6 REPEATABILITY AND REPRODUCIBILITY (R&R)

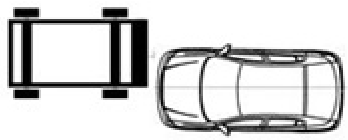
6.1 General

To study the repeatability and reproducibility within the limited MPDB test program in the FIMCAR project two sets of tests, carried out with identical Small Family Car 2 vehicles, are compared (see Figure 6.1).

To check repeatability, two tests carried out by TNO as part of the MPDB development project were used. Both tests were carried out with a trolley mass of 1500 kg, a test speed of 45 km/h and with the special developed MPDB trolley from TNO/TTAI.

To check reproducibility two tests of the FIMCAR project conducted at different test facilities were used. Both tests were carried out with a trolley mass of 1500 kg and a test speed of 50 km/h. One test was carried out by TTAI/TNO, using the special developed MPDB trolley from TNO/TTAI. The other test was carried out by IDIADA, using a modified ECE R95 trolley.

Lab	vehicle mass [kg]	MPDB mass [kg]	Closing speed [km/h]	Overlap
TNO F054801	1403	1500	90	50%
TNO F055001	1405	1500	90	50%
TNO F103904	1484	1512	100	50%
IDIADA 111410CF	1482	1500	100	50%



Reproducibility

Figure 6.1: MPDB tests used for R&R study.

6.2 Repeatability

The main results of the comparison of the repeatability test results are presented in Figure 6.3 Figure 6.3: Repeatability / B-pillar and trolley accelerations as well as Figure 6.4: Repeatability / delta-v of vehicle and trolley. The deformation of both vehicles are found to be similar, see Figure 6.2.

Figure 6.2: Repeatability / car deformation

All results show a very good repeatability (variations less than 5%) of the Small Family Car 2 tests carried out by TNO.

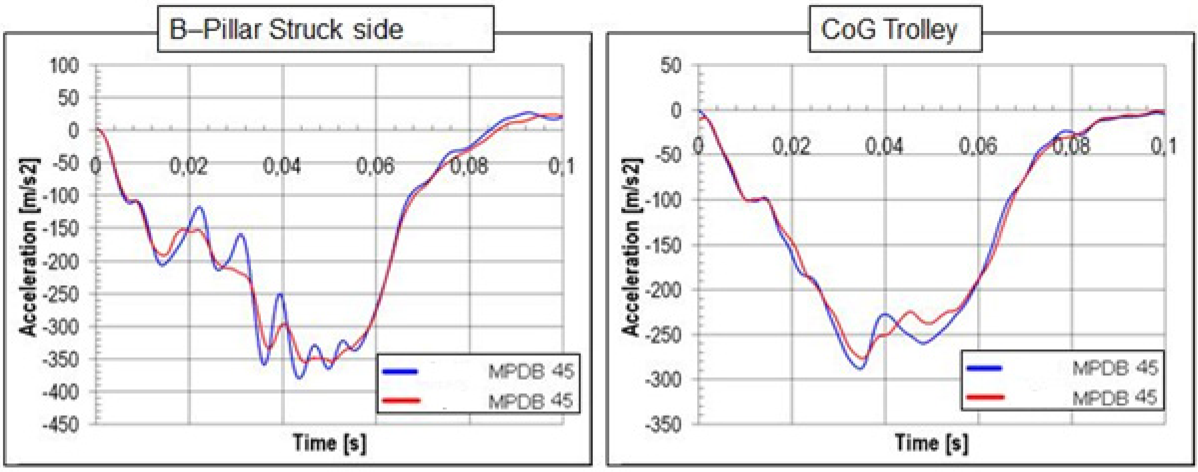
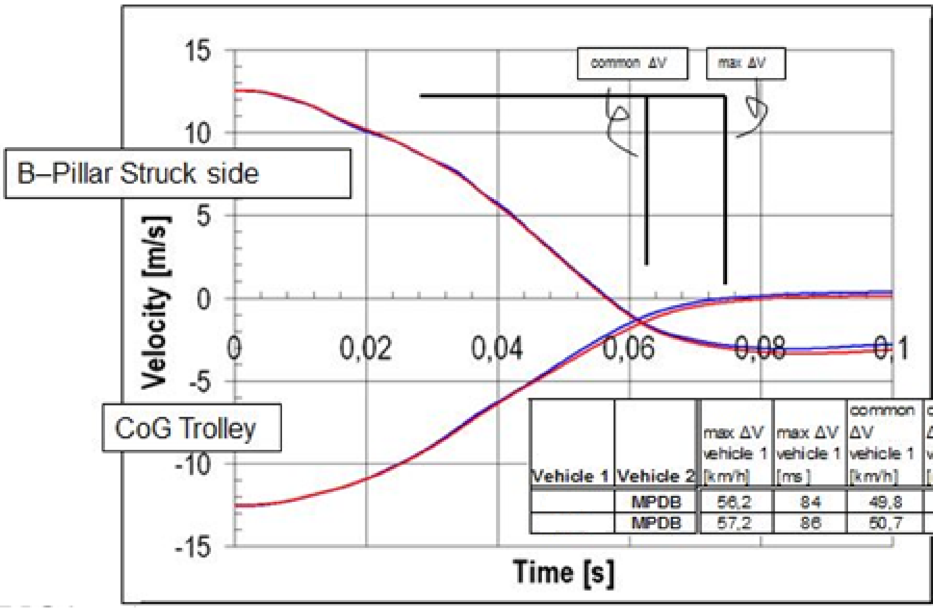


Figure 6.3: Repeatability / B-pillar and trolley accelerations.



Vehicle 1	Vehicle 2	max ΔV vehicle 1 [km/h]	max ΔV vehicle 1 [ms]	common ΔV vehicle 1 [km/h]	common ΔV vehicles [ms]	V0 passing vehicle 1 [ms]	Airbag firing time vehicle1 [ms]
	MPDB	56,2	84	49,8	61	57	14
	MPDB	57,2	86	50,7	62	57	15

Figure 6.4: Repeatability / delta-v of vehicle and trolley.

6.3 Reproducibility

The reproducibility tests were carried out as part of the FIMCAR project by TTAI/TNO and IDIADA, the test set up of both labs is presented in Figure 6.5. It is clearly visible that both laboratories use a different trolley to carry out the tests.

Original Test (TNO)

Reproducibility test (IDIADA)

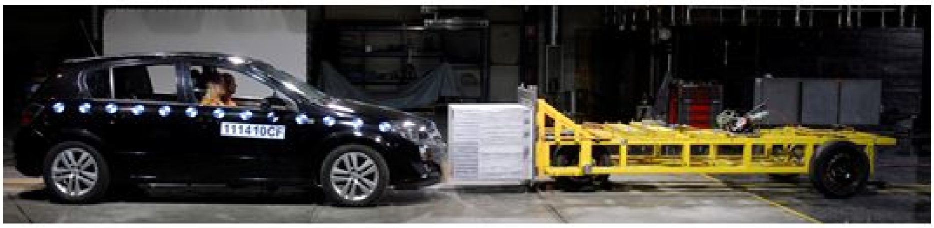


Figure 6.5: Reproducibility / test set up

The main results of the comparison of the reproducibility tests are presented in Figure 6.6 and Figure 6.7. The deformation of both vehicles is again similar as can be seen in Figure 6.8, the deformation of both PDB barriers is presented in Figure 6.9. The related DDY results are:

- TNO test : 2.96
- IDIADA test : 2.46

average : 2.71 ± 10%

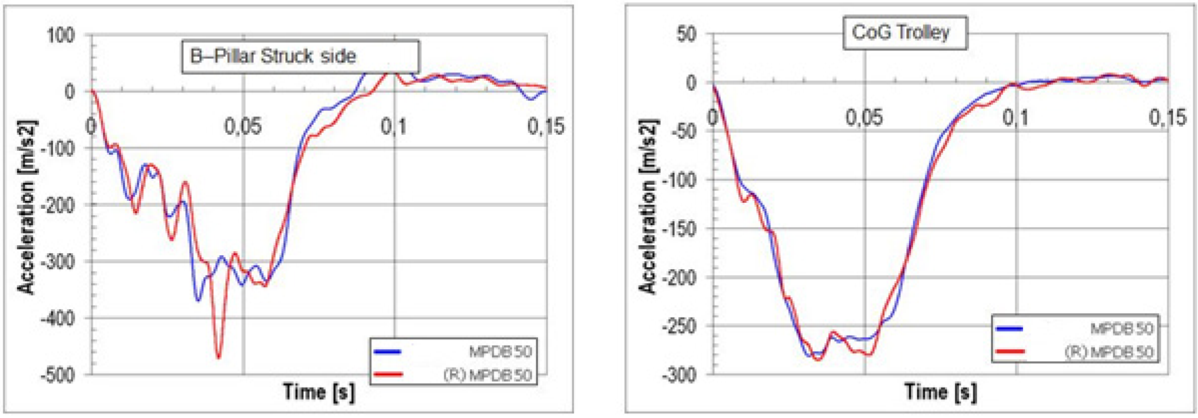
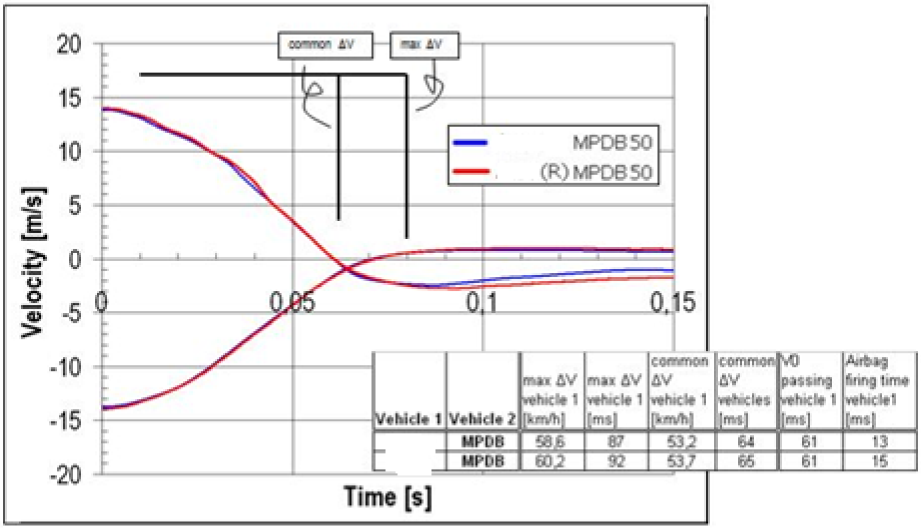


Figure 6.6: Reproducibility / B-pillar and trolley accelerations.



Vehicle 1	Vehicle 2	max ΔV vehicle 1 [km/h]	max ΔV vehicle 1 [ms]	common ΔV vehicle 1 [km/h]	common ΔV vehicles [ms]	V0 passing vehicle 1 [ms]	Airbag firing time vehicle1 [ms]
	MPDB	58,6	87	53,2	64	61	13
	MPDB	60,2	92	53,7	65	61	15

Figure 6.7: Reproducibility / delta-v of vehicle and trolley.

Figure 6.8: Reproducibility / vehicle deformations

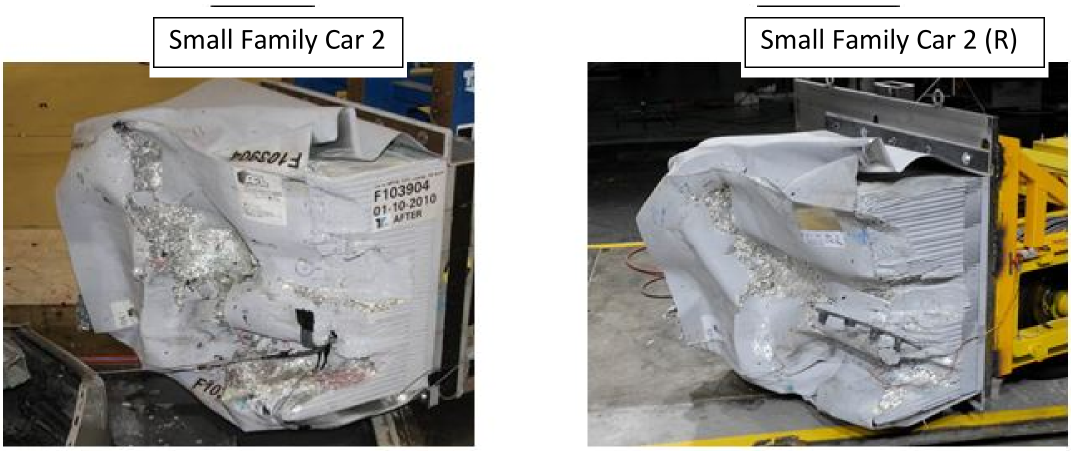


Figure 6.9: Reproducibility / PDB barrier deformation

For the reproducibility tests, the dummy results and vehicle deformation recordings were compared. An overview of the dummy results, presented in Euro NCAP layout, is shown in Figure 6.10. The A-pillar and B-pillar deformation of the tested vehicles, as recorded according to the Euro NCAP ODB protocol are presented in Figure 6.11. The Small Family Car 2 tested at IDIADA shows twice the A-pillar deformation, however this deformation is still far below the maximum level of 50 mm and may therefore be neglected.

It can be seen that the colour coding of the dummies is slightly different for both tests. This can be explained by the obtained injury values themselves. For body regions where the colouring is different, the injury reading is usually borderline with respect to the given colour. Therefore, slight changes in the actual value cause a shift in colouring. The overall score calculated per dummy is for both tests very similar.

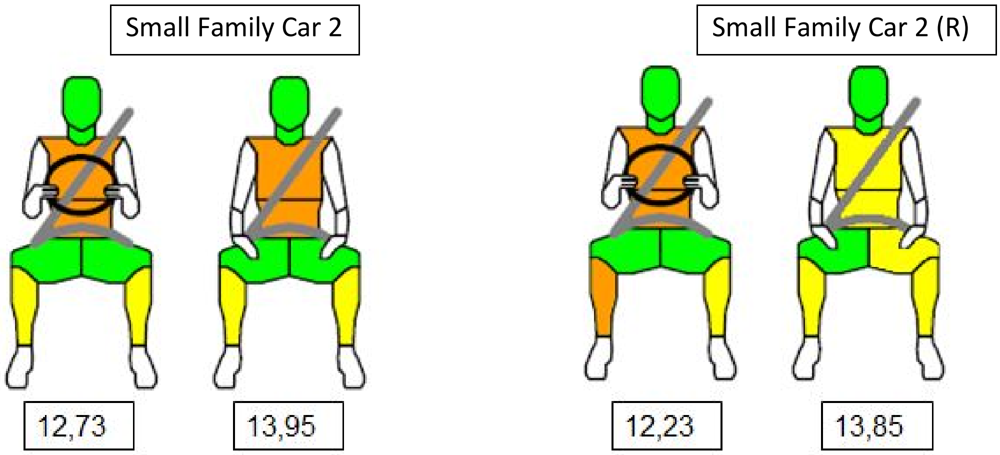


Figure 6.10: Reproducibility / dummy results (Euro NCAP layout)

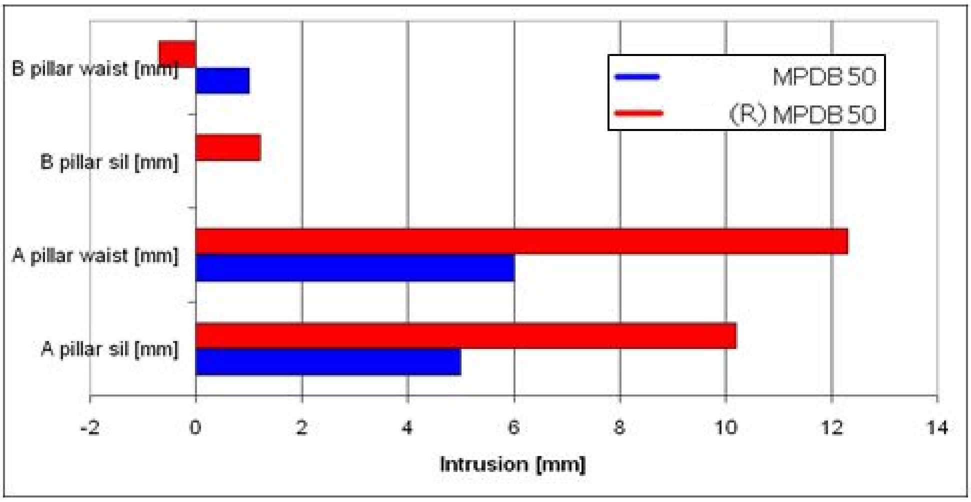


Figure 6.11: Reproducibility / vehicle deformations

7 DISCUSSION

7.1 Feasibility and Test Severity

As a mobile deformable barrier test (MDB test) procedure for compatibility testing is seen as the best method to evaluate car-to-car frontal crash behaviour by relevant groups in Europe [Uittenbogaard 2013 / Section IX] and the US [Hollowell 1999], a test protocol for such a test was developed within the FIMCAR project. It is believed, that this MDB test procedure provides a good base for harmonisation with efforts made by initiatives from other continents in the future.

As the development of a new deformable barrier was out of the scope of the FIMCAR project, the PDB barrier as used in WP2 “Offset test” was used for the MDB tests, which results in a so called MPDB test. Prior to conducting this test program a draft test protocol was defined in FIMCAR Deliverable D4.1 [Uittenbogaard 2013 / Section IX].

For the FIMCAR project 15 MPDB tests were carried out in five laboratories using four different trollies. From these 15 tests, 12 tests were carried out within the tight specifications of the draft protocol. For all the three tests outside the specifications an incorrect overlap/offset before impact was recognised as the only issue. One incorrect offset was due to an incorrect positioning of the vehicle and trolley prior test. The other two wrong offsets resulted most probably from an incorrect wheel alignment of test vehicle and/or trolley. In the future, extra attention is needed to check wheel alignment prior to the test. Also a change in the offset tolerance from ± 25 mm (for a static offset test) to ± 50 mm for a dynamic offset test (two moving objects) could be considered in the future.

Within the vehicle mass range used in the FIMCAR project, the kerb mass ranges from about 1000 kg to 2200 kg, the test severity of an MPDB tests with a trolley mass of 1500 kg and impact speed of 50 km/h is proposed. Based on B-pillar acceleration, delta-v, vehicle deformations and dummy values discussed in Chapter 3, the test is found comparable to the current R94 and Euro NCAP tests for heavy vehicles’, but more severe for average mass and light vehicles. However during the MPDB tests with the tested light vehicles most of the dummy results still fulfil most of the ECE R94 requirements. The severity of this proposal for heavy vehicles is also confirmed by the SUV 4 simulations carried out by VCC.

For vehicles outside the FIMCAR mass range, the test severity might be inappropriate: less severe (resulting in insufficient self-protection) for very heavy vehicles and too severe for very light vehicles, as for example new light weight electric urban vehicles. For these situations an adjustment of the test severity by means of changing the trolley mass and/or test speed could be necessary. Further investigation on this subject is needed from further future studies. Also the suggestion to test vehicles with a certain mass with a static PDB test instead of a MPDB test should be investigated further.

7.2 Compatibility Metrics

A metric based on the slope, or gradient, of barrier deformations in the lateral or vehicle Y axis proved to be the best candidate for a compatibility metric for MPDB tests. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

This candidate for an (M)PDB metric that assesses horizontal load spreading provides an objective method to assess structural interaction. The assessment was validated for the vehicles that can be clearly grouped into a good or poor performance category. There are a number of vehicles that are in a borderline area that require further evaluation. Further validation using field data and car-to-car test or simulation results can finalise the metric development.

While structural alignment and occupant compartment stability issues can be addressed with current ODB and proposed FWDB barrier recommendations in FIMCAR, there is no test procedure available that reliably assesses horizontal load spreading. The proposed DDY metric for the MPDB test allows the front structure for vehicles to be assessed and to be updated to also assess vertical load spreading

7.3 Repeatability and Reproducibility

Due to the limited FIMCAR test program a detailed investigation of repeatability and reproducibility was not possible. Only two repeated tests at one laboratory and 1 set of similar tests in 2 laboratories were conducted. From this brief investigation it was found, that both, repeatability as well as reproducibility were good, with test result variations less than 10%. In order to make a more well-grounded statement, further investigations (e.g. round robin tests) are needed.

8 CONCLUSION AND RECOMMENDATIONS

A draft test protocol for MPDB test was set up in the FIMCAR project. Using this protocol 15 tests were carried out. The results of these tests show that the test configuration is feasible in various laboratories. For this type of test, special attention is needed for the wheel alignment of trolley and test vehicles.

For the used mass range, kerb weight of 1000 kg to 2200 kg, a trolley mass of 1500 kg and test speed of 50 kg/h is proposed to define the required test severity. For vehicles outside this range, for example light electrical vehicles or heavy SUV's, an update of these specifications must be considered in the future.

Only two repeatability and two reproducibility tests were carried out. These series of tests both showed good results, giving an indication for good R&R, however, more tests are needed to make this statement statistically relevant

The metric for horizontal load spreading based on the deformation of the PDB barrier, as defined for the offset test of FIMCAR WP2, is also suitable for MPDB tests. This metric is based on the slope of barrier deformations in the lateral or vehicle Y axis. A horizontal assessment area based on 60% of half of the overall vehicle width and a vertical area between 305 and 555 mm was used. The 99%ile value for the Digital Derivative in Y (DDY) with a threshold value of 3.5 could discriminate between vehicle with an even (homogeneous) deformation pattern or a barrier with localised holes.

Discussion is needed if the MPDB test is a future test method with a possibility for global harmonisation or if it can replace the current ODB in a shorter term, as it has some advantages (adjustable trolley mass / test severity) above the PDB offset test. These advantages are in principle able to overcome obstacles for the introduction of the PDB test, e.g. the test severity for heavy cars can be increased if felt necessary.

Investigations are needed if the proposed metric for horizontal load spreading can be extended to a metric for vertical load spreading.

9 REFERENCES

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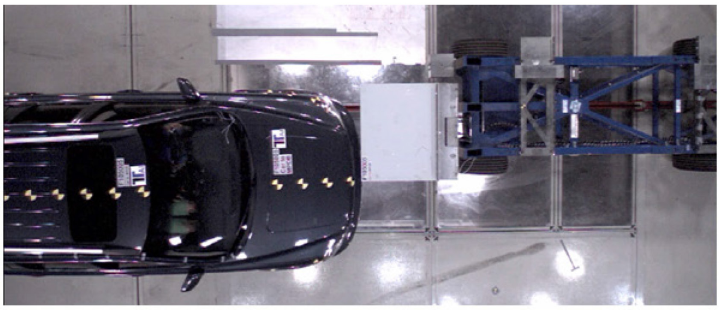
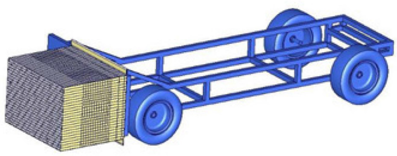
APPENDIX A: SUV 4 SIMULATION RESULTS

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study **FXX-11-300**

FIMCAR
WP4 SUV 4 activities

Car-to-MPDB simulations
Linus Wågström, Volvo Cars Safety Centre
2012-09-18





Barrier model:
PDB_June20_2011_version2.key

Trolley model:
VCC modified side impact trolley
see Appendix for more information

Part 1

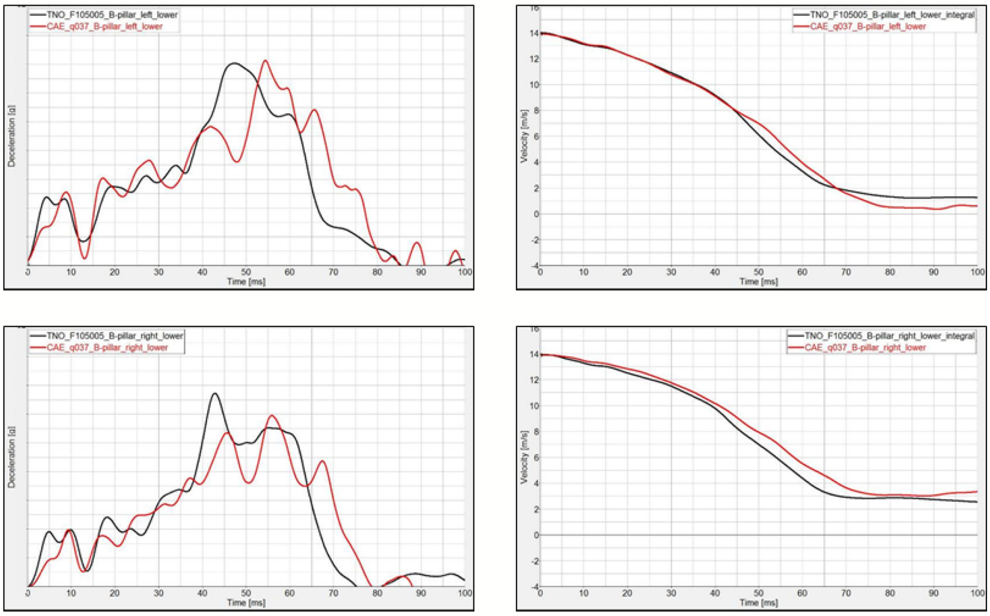
Baseline model validation
Trolley 1500 kg / closing speed 100 km/h
CAE model q037 vs. TNO test 105005

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study FXX-11-300

SUV 4 crash pulses and velocity profiles

LHS sill
Struck

RHS sill
Non-struck



Accelerations filtered with SAEJ211/CFC60

CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
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Date: 2012-09-18
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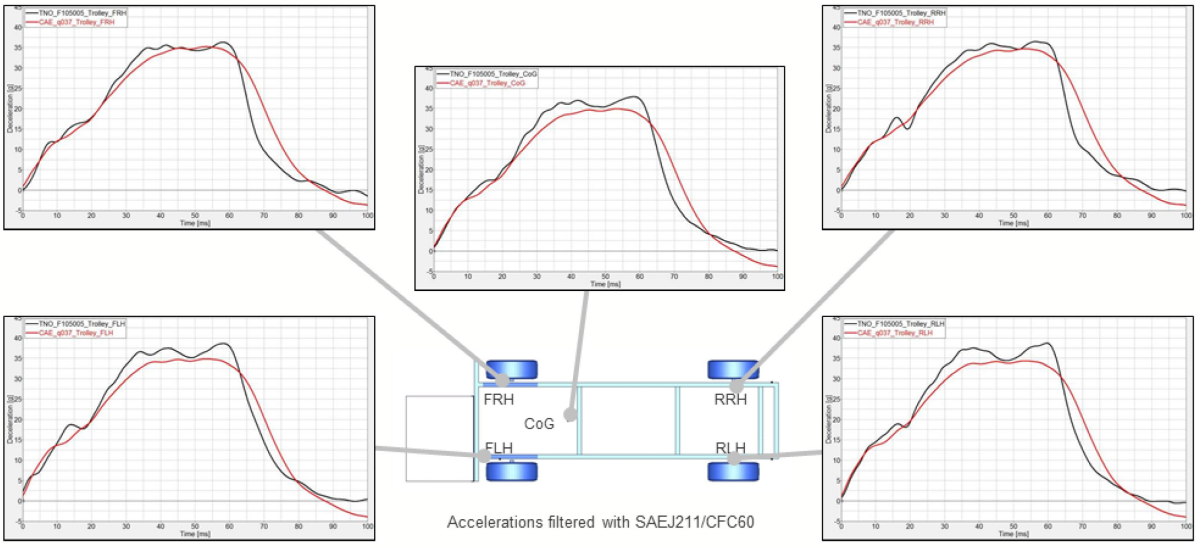
CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study FXX-11-300

Trolley crash pulses



Accelerations filtered with SAEJ211/CFC60

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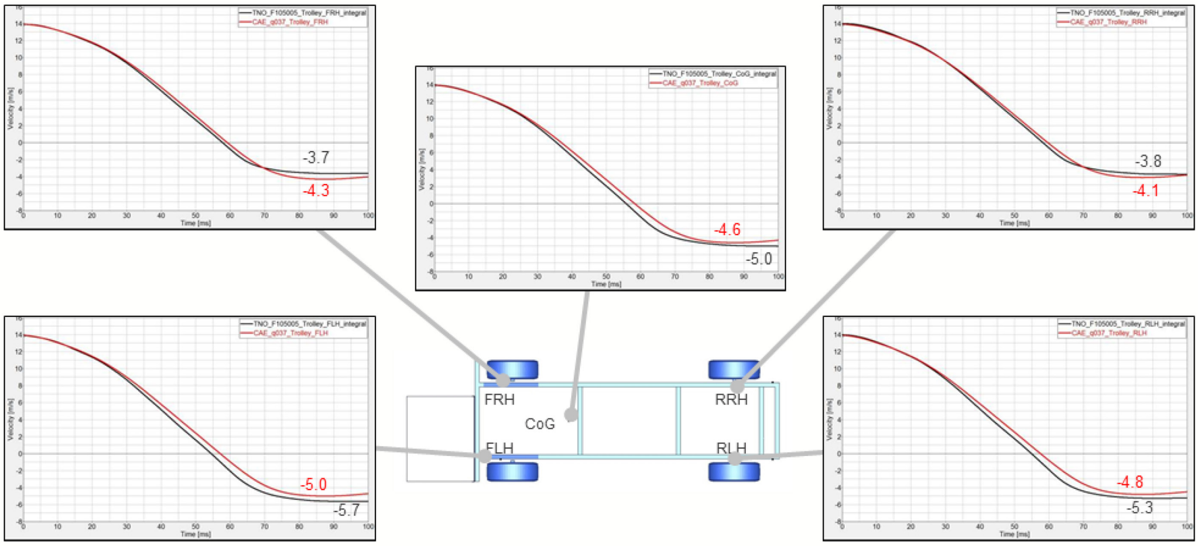
Trolley velocity profiles



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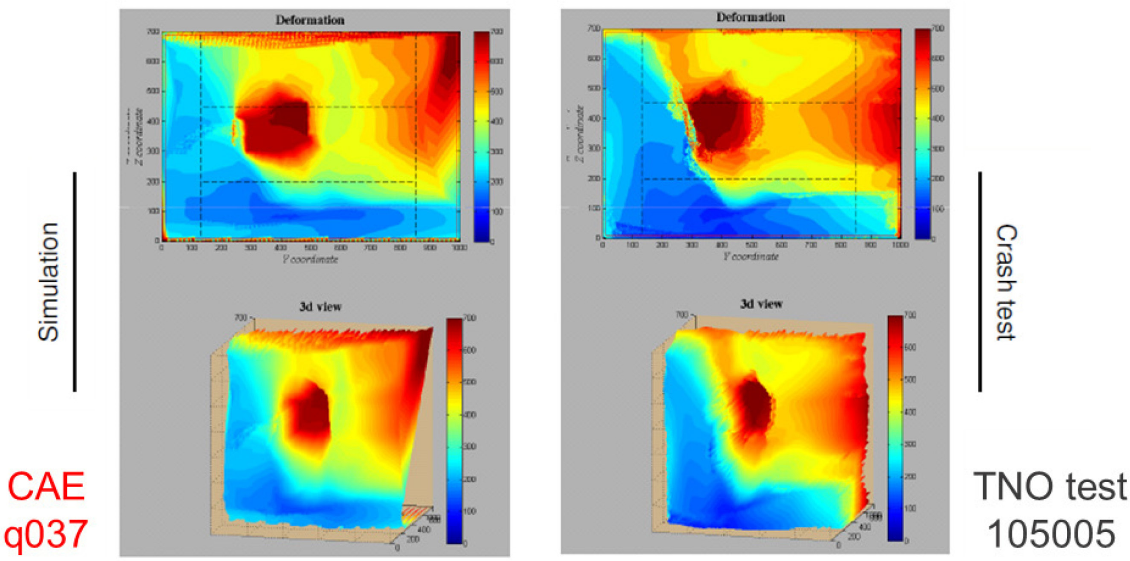
Barrier deformation



Picture from TU Berlin evaluation

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Conclusions - Part 1:

- CAE model captures car crash pulses and velocity profiles. Some timing differences when comparing CAE and test.
- CAE model captures trolley crash pulses and velocity profiles. Test generally shows slightly higher acceleration.
- Barrier deformation very similar in simulation compared to test. Acceleration curves suggest that PDB CAE model should be stiffened slightly.

Overall, the results indicate sufficient model quality to proceed with the parameter study in Part 2.

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Part 2

Parameter study

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Simulation matrix

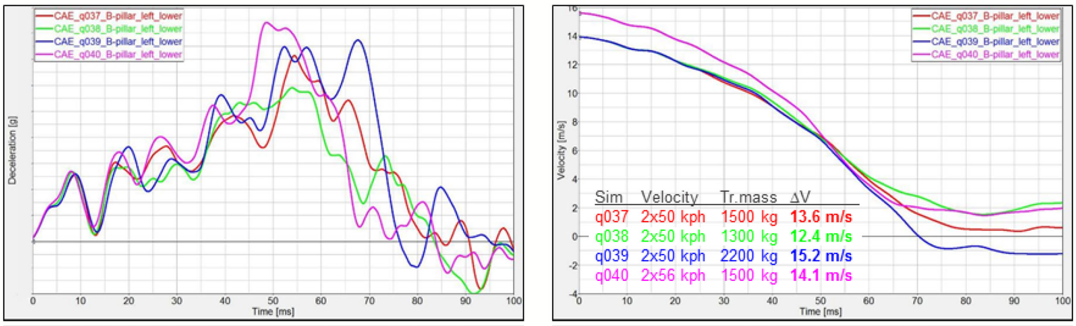
	Simulation	Barrier	Car velocity [kph]	Barrier velocity [kph]	Relative velocity [kph]	Barrier mass [kg]	Car mass [kg]	Initial kinetic energy [kJ]
Baseline	⇨SUV 4_fimcar_q037	MPDB	50	50	100	1500	2400	376
	SUV 4_fimcar_q038	MPDB	50	50	100	1300		357
	SUV 4_fimcar_q039	MPDB	50	50	100	2200		444
	SUV 4_fimcar_q040	MPDB	56	56	112	1500		472
Euro-NCAP	⇨SUV 4_fimcar_o041	ODB	64		64			379
R94	⇨SUV 4_fimcar_n041	ODB	56		56			290
Fixed PDB	⇨SUV 4_fimcar_q042	PDB	60		60			333

Project: FIMCAR
Load cases: q - MPDB LHD, o - ODB LHD
Code version: LS DYNA mpp 971 sR4.2.1.

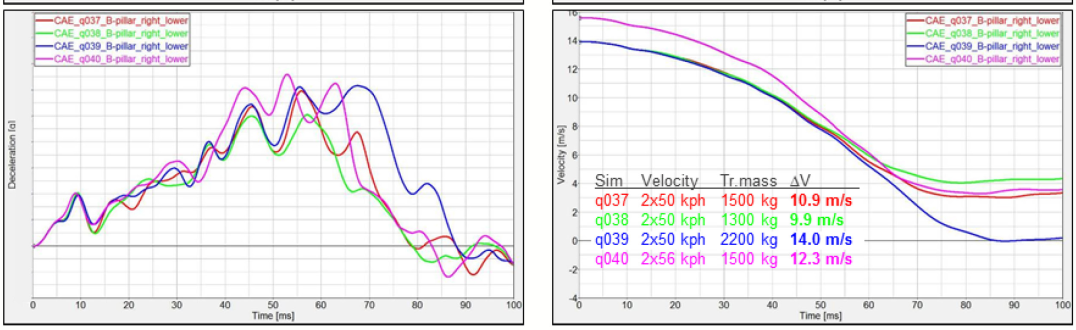
CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study **FXX-11-300**

SUV 4 crash pulses and velocity profiles

LHS sill *Struck*



RHS sill *Non-struck*



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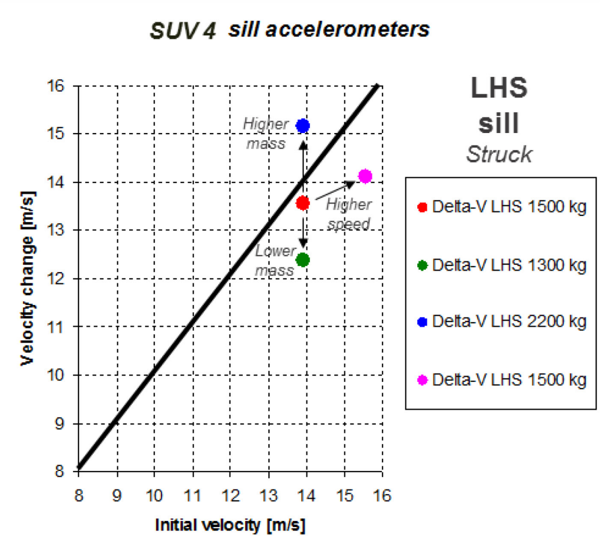
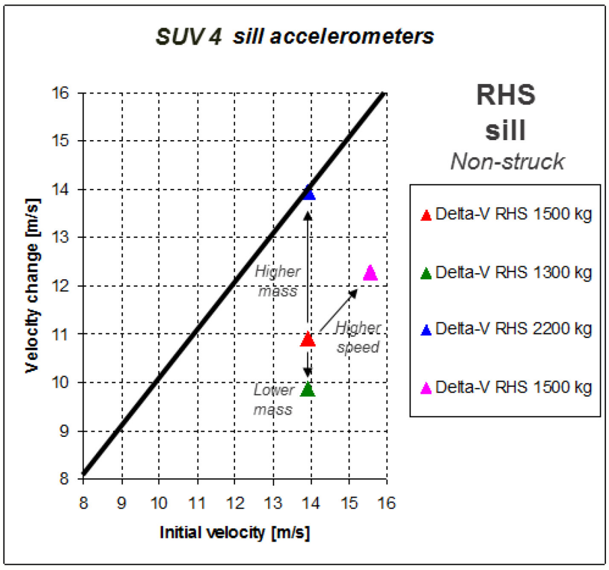
SUV 4 overview of velocity change vs. initial velocity





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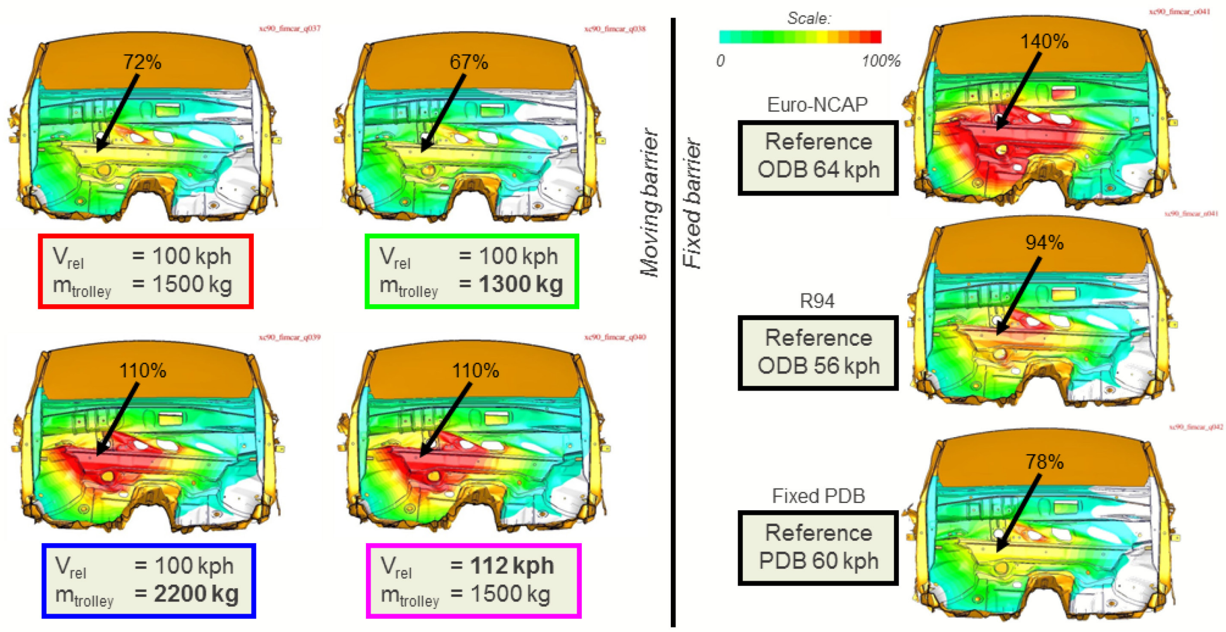
SUV 4 passenger compartment max dynamic intrusion (normalised)



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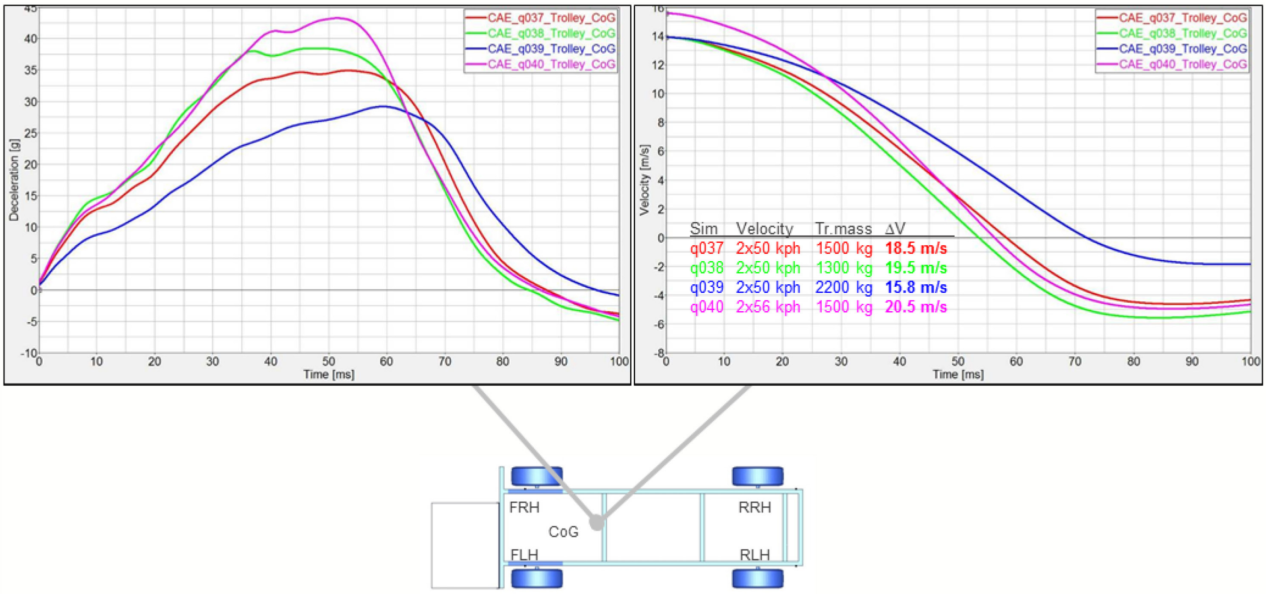
Trolley CoG crash pulses and velocity profiles



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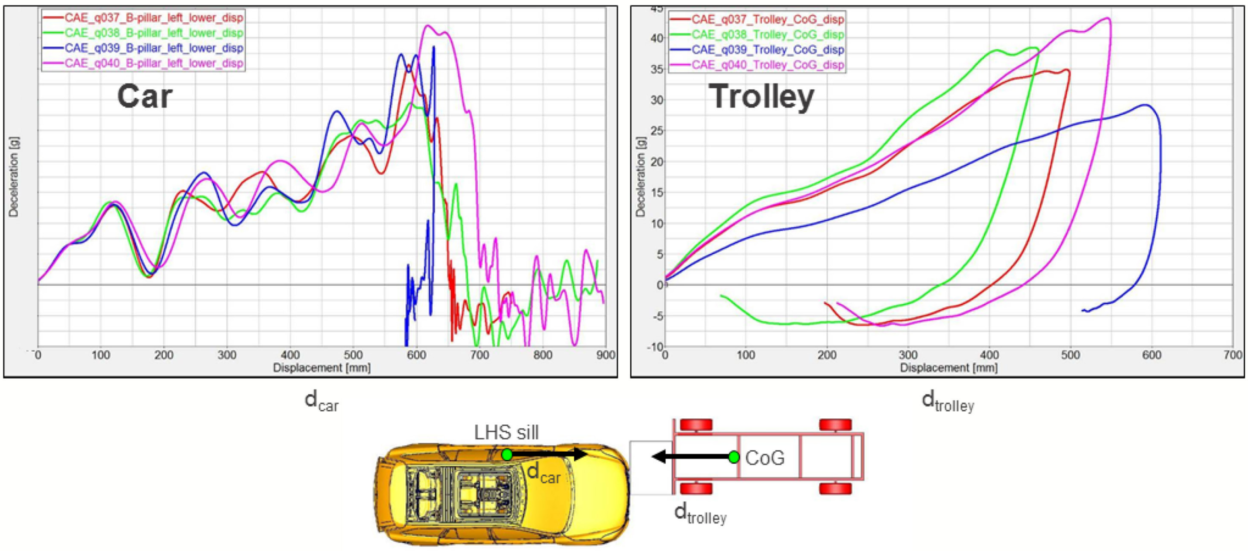
Car and trolley crash pulses vs. displacement



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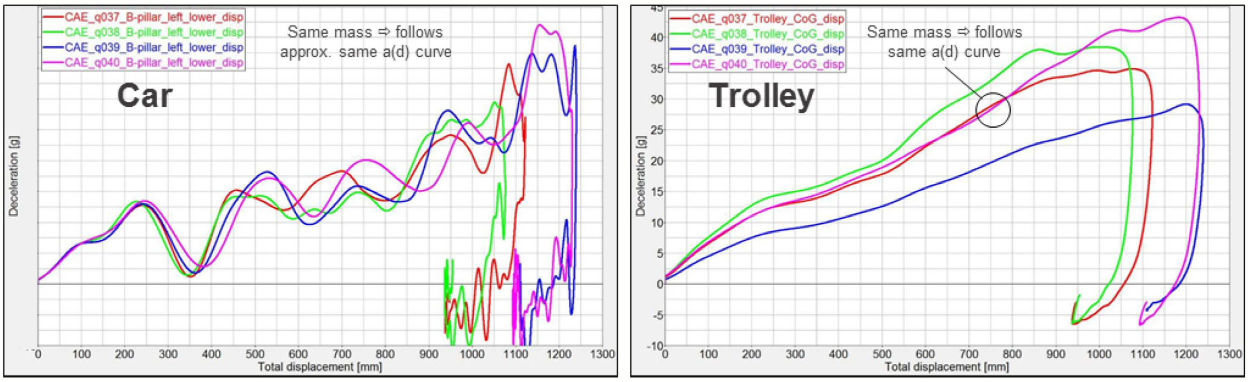
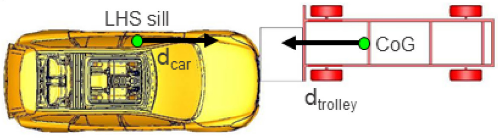
Car and trolley crash pulses vs. displacement

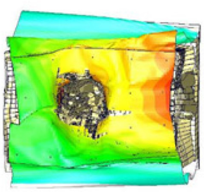


$d_{car} + d_{trolley}$ $d_{car} + d_{trolley}$

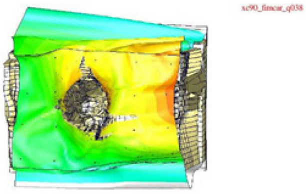


CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study FXX-11-300

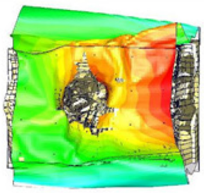
Barrier deformation at 150 ms (i.e. with rebound)



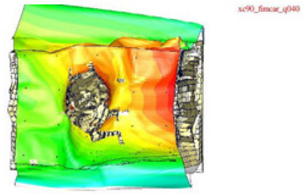
V_{rel} = 100 kph
$m_{trolley}$ = 1500 kg



V_{rel} = 100 kph
$m_{trolley}$ = **1300 kg**

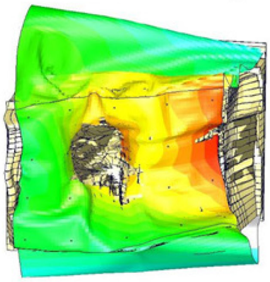


V_{rel} = 100 kph
$m_{trolley}$ = **2200 kg**



V_{rel} = **112 kph**
$m_{trolley}$ = 1500 kg

Moving barrier | *Fixed barrier*



Reference
PDB 60 kph

Scale:

0 *600 mm*

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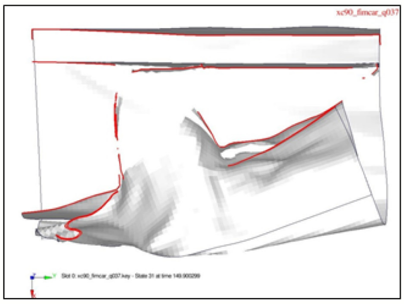
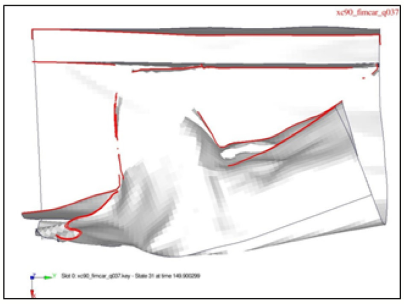
Barrier deformation at 150 ms (i.e. with rebound)

V_{rel} = 100 kph
$m_{trolley}$ = 1500 kg



V_{rel} = 100 kph
$m_{trolley}$ = 1500 kg



V_{rel} = 100 kph
$m_{trolley}$ = 1500 kg

Cross section at z = 770 mm
Flip between pages to see difference

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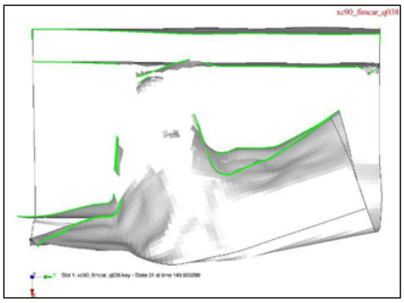
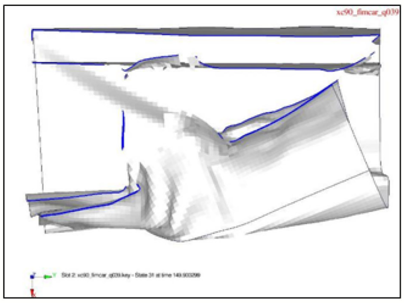
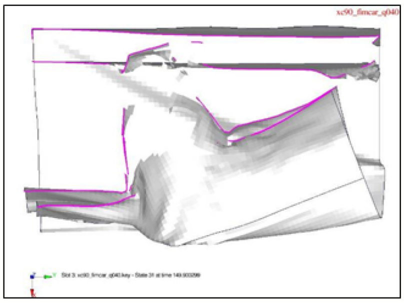
Barrier deformation at 150 ms (i.e. with rebound)



V_{rel} = 100 kph
$m_{trolley}$ = **1300 kg**



V_{rel} = 100 kph
$m_{trolley}$ = **2200 kg**



V_{rel} = **112 kph**
$m_{trolley}$ = 1500 kg

Cross section at z = 770 mm
Flip between pages to see difference

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PDB energy dissipation and EES

	Sim #	Relative velocity [km/h]	Trolley mass [kg]	Total kinetic energy [kJ]	Total dissipated energy [kJ]	PDB dissipated energy [kJ]	PDB share of dissipated energy	EES [km/h]
Moving barrier	q037	100	1500	376	345	186	54%	**42.9**
Moving barrier	q038	100	1300	357	317	177	56%	**40.1**
Moving barrier	q039	100	2200	444	426	213	50%	**49.9**
Moving barrier	q040	112	1500	472	433	220	51%	**49.4**
Fixed barrier	q042	60	N/A	333	308	171	55%	**41.9**

Formulas used for EES

$$E_{to\_absorb} = \frac{1}{2} \cdot \frac{m_{car} \cdot m_{trolley}}{m_{car} + m_{trolley}} \cdot v_{rel}^2$$

This energy is the initial kinetic energy when normalised for equal momentum

$$E_{abs} = E_{to\_absorb} - E_{barrier}$$

$$EES(km/h) = 3.6 \times \sqrt{\frac{2 \times Eabs}{M}} \quad (1a).$$

Eabs = energy absorbed by the vehicle (J)
Eabs = Kinetic energy – Energy in the barrier
M = mass of the vehicle (kg) Here: 2400 kg

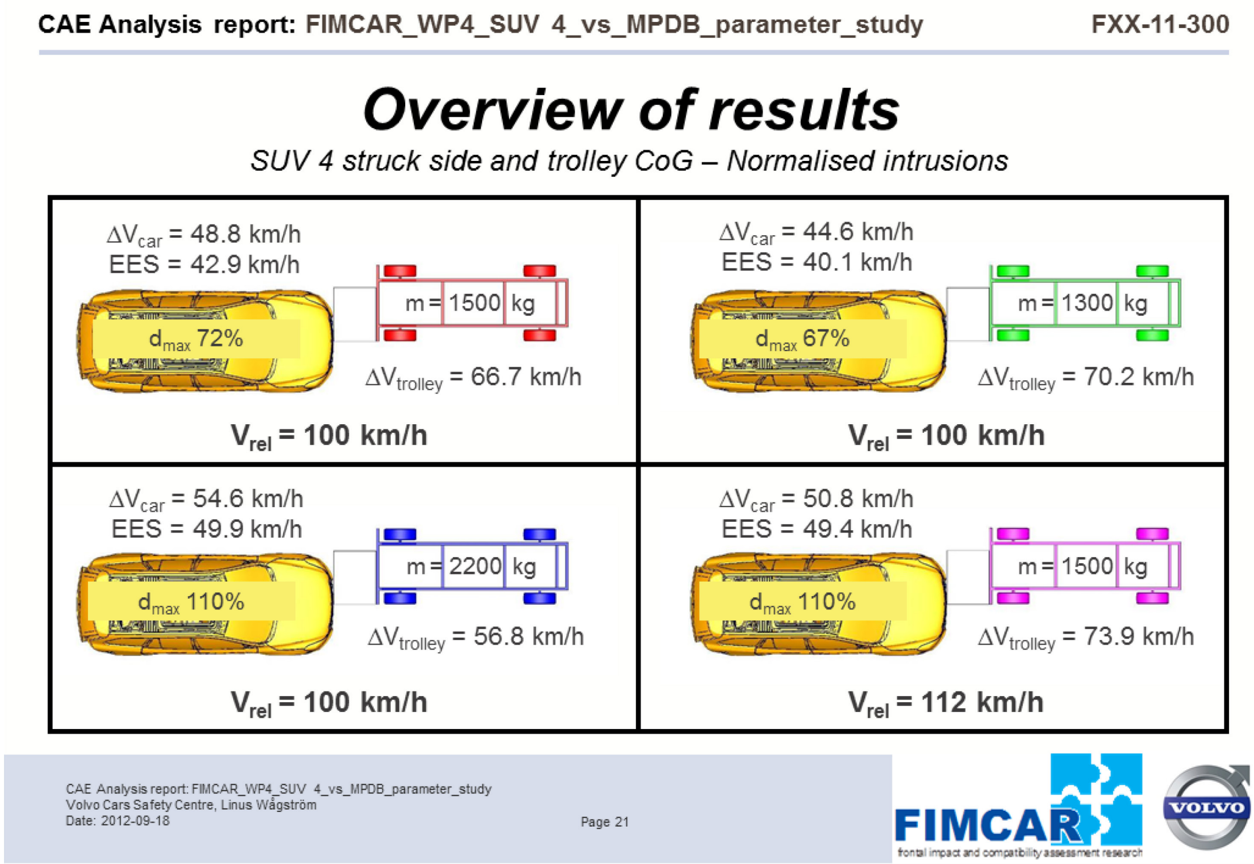
Conclusions - Part 2 (see also next slides):

In terms of SUV 4 passenger compartment intrusions and EES:

- Small differences between 1500 kg and 1300 kg trolley, both give lower intrusion than ODB at 56 kph.
- Similar results using 2200 kg trolley at 100 kph closing velocity compared to 1500 kg at 112 kph.
- Out of the tested variants, the baseline car-to-MPDB (1500 kg trolley at 100 kph closing velocity) is most similar to fixed PDB
- All car-to-MPDB show lower intrusion than Euro-NCAP test

In terms of SUV 4 velocity change:

- Higher velocity change using 2200 kg trolley at 100 kph closing velocity compared to 1500 kg at 112 kph.


CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
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Overview of results
SUV 4 struck side and trolley CoG – Normalised intrusions
ΔVcar = 48.8 km/h
EES = 42.9 km/h
m = 1500 kg
dmax 72%
ΔVtrolley = 66.7 km/h
Vrel = 100 km/h
ΔVcar = 44.6 km/h
EES = 40.1 km/h
m = 1300 kg
dmax 67%
ΔVtrolley = 70.2 km/h
Vrel = 100 km/h
ΔVcar = 54.6 km/h
EES = 49.9 km/h
m = 2200 kg
dmax 110%
ΔVtrolley = 56.8 km/h
Vrel = 100 km/h
ΔVcar = 50.8 km/h
EES = 49.4 km/h
m = 1500 kg
dmax 110%
ΔVtrolley = 73.9 km/h
Vrel = 112 km/h
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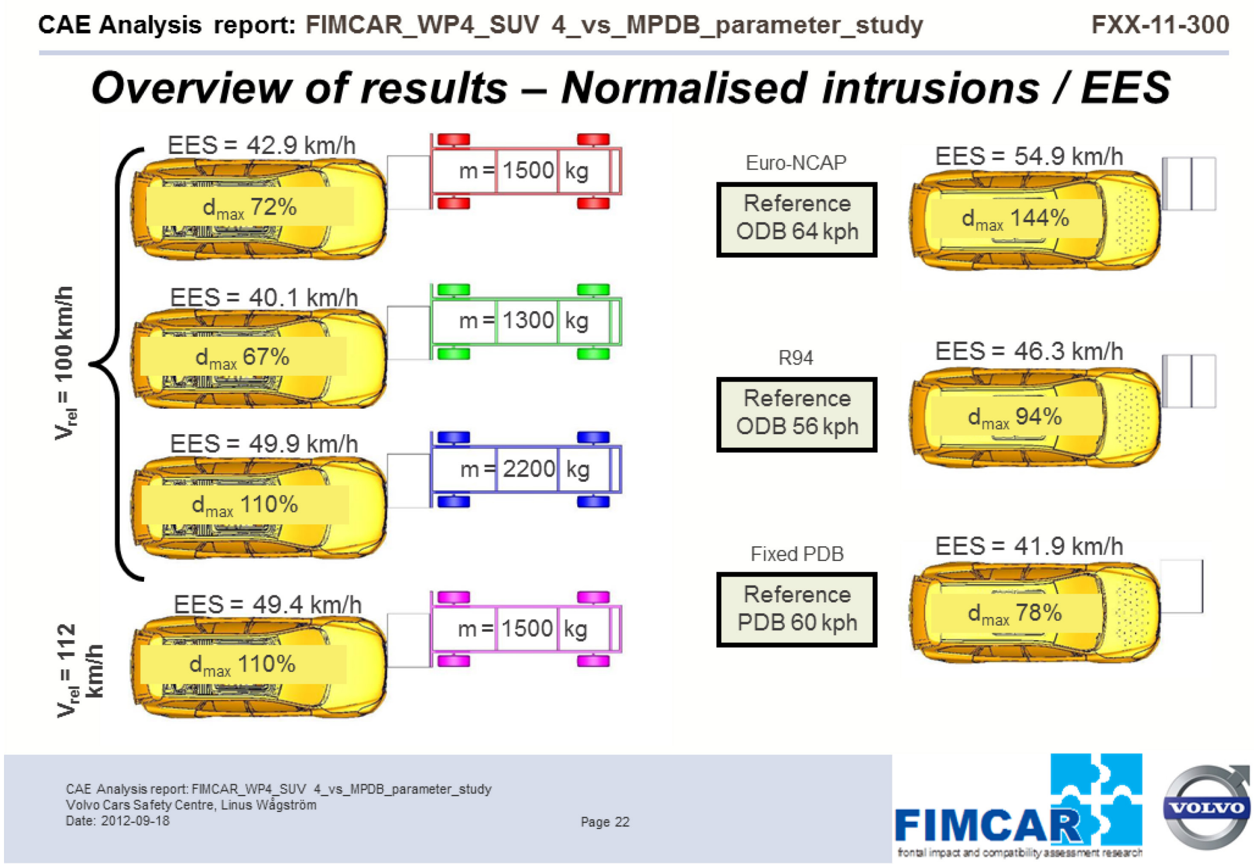
CAE Analysis report: FIMCAR_WP4_SUV 4_vs_MPDB_parameter_study
FXX-11-300
Overview of results – Normalised intrusions / EES
EES = 42.9 km/h
m = 1500 kg
dmax 72%
EES = 40.1 km/h
m = 1300 kg
dmax 67%
EES = 49.9 km/h
m = 2200 kg
dmax 110%
Vrel = 100 km/h
EES = 49.4 km/h
m = 1500 kg
dmax 110%
Vrel = 112 km/h
Euro-NCAP
Reference ODB 64 kph
EES = 54.9 km/h
dmax 144%
R94
Reference ODB 56 kph
EES = 46.3 km/h
dmax 94%
Fixed PDB
Reference PDB 60 kph
EES = 41.9 km/h
dmax 78%
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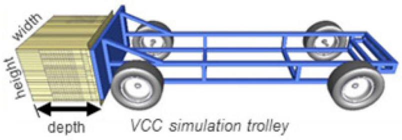
Appendix:
Trolley comparison

Test trolley



VCC simulation trolley

Physical data from TNO
2011-02-23

Description	Unit	TNO Physical values	VCC CAE model	Δ
Mass	[kg]	1500	1501	0%
Mass front axle	[kg]	1100	1116	1%
Mass rear axle	[kg]	400	385	-4%
Barrier height	[m]	0.70	0.70	0%
Barrier width	[m]	1.00	1.00	0%
Barrier depth, extended	[m]	0.8	0.78	-3%
Barrier ground clearance	[mm]	150	150	0%
Overall Length	[m]	4.35	4.37	0%
Axle height	[m]	0.28	0.3	7%
Wheel base	[m]	2.60	2.60	0%
Track width, centerline of wheels	[m]	1.20	1.20	0%
CoG x-dir from front (extended)	[mm]	2000	1917	-4%
CoG x-dir from frontal axle	[mm]	700	676	-3%
CoG y-dir from trolley centerline	[mm]	0	5	
CoG z-dir from ground	[mm]	600	602	0%
Iyz Roll	[kg·m²]	550	560	2%
Ixz Pitch	[kg·m²]	2550	2520	-1%
Ixy Yaw	[kg·m²]	2650	2650	0%
Tyre pressure	[bar]	2.5	2.5	0%
Tyres		205/55		
Barrier face location		Left outlined with outside of wheels		

Robert Thomson, Heiko Johannsen, Mervyn Edwards, Thorsten Adolph, Ignacio Lazaro, Ton Versmissen

SEVENTH FRAMEWORK PROGRAMME

FIMCAR
XI – FIMCAR Final Assessment Approach

FIMCAR
frontal impact and compatibility assessment research

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CONTENTS

EXECUTIVE SUMMARY

The objectives of the FIMCAR (Frontal Impact and Compatibility Assessment Research) project are to answer the remaining open questions identified in earlier projects (such as understanding of the advantages and disadvantages of force based metrics and barrier deformation based metrics, confirmation of specific compatibility issues such as structural interaction, investigation of force matching) and to finalise the frontal impact test procedures required to assess compatibility. Research strategies and priorities were based on earlier research programs and the FIMCAR accident data analysis. The identified real world safety issues were used to develop a list of compatibility characteristics which were then prioritised within the consortium. This list was the basis for evaluating the different test candidates. This analysis resulted in the combination of the Full Width Deformable Barrier test (FWDB) with compatibility metrics and the existing Offset Deformable Barrier (ODB) as described in UN-ECE Regulation 94 with additional cabin integrity requirement as being proposed as the FIMCAR assessment approach.

The proposed frontal impact assessment approach addresses many of the issues identified by the FIMCAR consortium but not all frontal impact and compatibility issues could be addressed.

1 INTRODUCTION

1.1 FIMCAR Project

To improve real life f vehicle safety in frontal collisions, the compatibility (described by the self and partner-protection level) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition, another procedure (tests with a moving deformable barrier) is under discussion in today's research programmes.

Within the FIMCAR project, different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations. The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work Package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to describe the testing and assessment procedures for a frontal impact and compatibility test procedure. The deliverable describes the procedures and criteria used to evaluate the different candidate procedure. A summary of the technical results is provided but references to critical technical documents are also identified for further review.

1.3 Structure of this Deliverable

The deliverable is divided into the first chapters describing the decision process and the selection criteria for the different assessment procedure that should be combined into the FIMCAR assessment approach. The advantages and disadvantages of the different candidates and the justification for the FIMCAR decisions are also presented Following this, the FIMCAR assessment approach is presented in an ECE like document, which can be used as a first draft for rule making.

2 BACKGROUND

Passive safety in frontal impacts has been addressed through different regulation and consumer testing in the world. Regulation 94 and Euro NCAP in Europe; FMVSS 208, USNCAP and IIHS in the US; TRIAS-47 and JNCAP in Japan are some of the best known examples internationally. All tests evaluate the passive safety of a vehicle in a fixed barrier configuration but do not consider collisions with another vehicle that has different structural and mass properties. This issue has been investigated by many research groups but, to date, no combined partner and self protection assessment procedure has been developed and validated in Europe, Asia, or North America.

Crash compatibility sometimes is a compromise between self and partner protection and it is important to not sacrifice one for the sake of the other. Compatibility will be used in the following document as a concept that is a combination of both self and partner protection. Individual compatibility characteristics are identified that address only one aspect of frontal impacts i.e. self or partner protection. The test procedures presented in this deliverable may address one or more of these characteristics.

2.1 Previous Research

Compatibility research is globally distributed with the research activities taking place predominantly in US, Japan and Europe. In all these areas, the activities are distributed between industry and government funded research activities. Different test methods have been investigated in the different regions but the global consensus in the IHRA compatibility working group [O'Reilly 2003] was that both an off-set and a full width test are needed to fully assess compatibility and frontal protection performance. Each region has unique compatibility issues related to their respective traffic fleets, but similar strategies and approaches can be observed. Consistent with the need to address both full width and off-set test configurations for compatibility testing, a number of alternatives are available for further development. An overview of the activities previous to FIMCAR is provided below.

2.1.1 Europe

European compatibility research has been undertaken at various research centres but the most significant activities have been coordinated by or reported to the EEVC WG15 (European Enhanced Vehicle Safety Committee Working Group on Car Crash Compatibility and Frontal Impact). This working group finished a mandate to investigate the test procedures needed to assess crash compatibility [Faerber 2007]. The working group results confirm that improving compatibility will have positive cost benefit results for Europe. Test methods to detect and assess compatibility were investigated with a focus on developing structural interaction assessments. The difficulty in defining an objective test approach for structural interaction was encountered by the working group. A list of open questions was developed by the working group identifying the next steps needed to finalise compatibility test approaches.

One recent activity to note is the development of a moving deformable barrier test using a deformable element. This test method has been put forward by many researchers in Europe, USA, and Japan as a long term solution to compatibility and has been reported previously [Summers 2002, Seyer 2003, Versmissen 2006].

2.1.2 USA

Compatibility issues in the US are dominated by LTV/SUV impacts with smaller passenger cars. The most noteworthy development has been the industry voluntary commitment (coordinated through the Alliance of Automobile Manufacturers) [Auto Alliance 2003] to provide overlapping structures in frontal impacts, particularly in LTV to passenger car impacts. The commitment was initiated in 2003 and required 100% compliance for vehicle geometric designs by 2009. Parallel to the geometric requirement for structures, research into the parameters controlling compatibility has been investigated, including physical test requirements. One of the test methods under investigation is the high resolution load cell barrier that measures the force distribution over the vehicle front during a full width barrier test. This test approach is also under investigation by NHTSA and metrics such as the Average Height of Force (AHOF), Initial Stiffness (Ks), and Work Stiffness (Kw) have been derived from this type of test data and correlated to real world crashes [Summers 2005]. The US stakeholders have focussed their research efforts on the full width rigid barrier because it is the foundation of its frontal impact regulation. Most full width tests and analyses in the US have been for rigid barrier face.

Further work in frontal compatibility testing has been proposed in the Auto Alliance expert working group. The implementation of a moving deformable barrier for frontal crash testing had been investigated since the 1990's and has now been reviewed as method to control the frontal force levels in vehicles as well as addressing structural interaction. Further developments of this MDB have not been reported since 2008 although an application of a MDB for small overlap conditions has been under development [Saunders 2012].

2.1.3 Japan

The Japanese vehicle fleet, similar to Europe, is not characterised by a large LTV/SUV population that is found in the US. However, a particular difference in the Japanese and European vehicle fleet is the presence of so called mini cars in Japan that are designed to offer maximum internal space for a limited vehicle length. These cars normally have their bumper directly in front of the engine and do not incorporate any kind of crush can in the design because repair tests i.e. the RCAR bumper test, are not applicable. Legislative and consumer tests in Japan are based on the Full Width Rigid Barrier test and the recent adoption of the R94 offset test. The Japan Automobile Research Institute (JARI) as well as Honda has presented recent investigations of the use of load cell wall data as a method to assess compatibility. Alternative test approaches (with or without deformable honeycomb barriers) have been assessed and compared to car-to-car tests.

The Japanese automobile industry has investigated different testing or evaluation approaches. Toyota has researched the moving deformable barrier test for frontal impacts, partly in conjunction with the US industry research activities, and has developed a specific deformable element more complex than the EEVC (current ECE R94 barrier face) or PDB barrier element. Analysis of load cell wall data from a full width test has also been proposed [Yonezawa 2011].

2.1.4 Objectives for FIMCAR

The FIMCAR project was designed to investigate the possibility of combining different configurations to assess compatibility. These tests are the Full Width Rigid Barrier (FWRB), Full Width Deformable Barrier (FWDB), Offset Deformable Barrier (ODB), Progressive Deformable

Barrier (PDB) and a Mobile Deformable Barrier (MDB). A general description of the available test procedures are provided below. The reader is referred to [Adolph 2012] for detailed descriptions of each of the candidate test procedures.

- Full width load cell barrier tests: The test is effectively a modification of the US FMVSS-208 full width test used for the assessment of self protection. The test is modified by the addition of a high resolution Load Cell Wall. The test should control both partner and self protection. For partner protection, the car's structural interaction potential will be assessed using the measurements from the LCW. Configurations of the test, with and without a deformable honeycomb element are being examined by different research communities. The test configuration is focused on the measurement of structural interaction as well as introducing a high overlap, high deceleration to assess occupant restraint systems.
- Off-set barrier tests: The current off-set test approaches, most common in vehicle testing, are used in the European frontal directive (96/79/EC) and in consumer tests like Euro NCAP. These consist of an impact into a honeycomb barrier (EEVC barrier) with a 40% overlap. There are no current activities investigating the use of this test configuration for measuring structural interaction, but frontal force levels have been measured using a load cell wall mounted behind the deformable element and was investigated previously [Edwards 2007]. Another off-set test procedure – the Progressive Deformable Barrier (PDB) – has been investigated for structural interaction and frontal force level assessment. This 50% off-set test condition measures the deformation of the honeycomb barrier after the test. The PDB honeycomb is stiffer than the EEVC barrier and becomes progressively stiffer with increased deformation. The barrier deformation is used to analyse the structural interaction and force levels of the tested vehicle.
- Moving Deformable Barrier Tests: A frontal impact test using a deformable barrier element mounted on a moving trolley has been investigated, primarily to assess and control frontal force levels. In fixed barrier tests like the full width and off-set tests, the initial kinetic energy of the test vehicle must be absorbed in the deformation of the vehicle and the barrier. In a moving barrier test, the kinetic energy and momentum are distributed between the vehicles depending on the vehicle mass. This allows the test to evaluate vehicles for different conditions depending on their mass.

Based on previous research work towards compatibility (e.g., EUCAR Compatibility project [Zobel 2001], EEVC WG15 [Faerber 2007], VC-COMPAT [Edwards 2007] and other international and national research projects and working groups), the main issues for improving compatibility are:

- Structural interaction
- Global force level matching
- Compartment strength and stability

The two most challenging compatibility issues were those of *structural interaction* and *global force matching.* Structural interaction describes how the contact forces are distributed across collision partners and the stability of the crash response. Good structural interaction is not commonly found in modern vehicles due the differences in vehicle sizes and crashworthiness designs. Poor structural interaction leads to phenomena such as over/underride or fork effect which in turn lead to undesirable deformation and intrusion of the occupant compartment. Frontal force level matching is desirable to ensure that crash energy is appropriately shared between collision partners. Current international consumer and regulation test methods cause frontal crush forces to be mass dependent and require heavier vehicles to be stiffer than lighter vehicles. Earlier studies found this disparity in vehicle force levels caused heavier vehicles to over-crush lighter vehicles and again produce undesired occupant compartment deformations. The two compatibility characteristics described above require a *strong and stable occupant compartment* to support energy absorption in frontal structures.

One explanation for the lack of progress in compatibility can be the terminology and individual definitions used when discussing compatibility. An improved and more detailed description of compatibility characteristics is a key point to base any research project that addresses compatibility. For example, structural interaction can likely be divided into different sub areas dealing with geometrical placements of structures or the way structures are internally distributing loads in the car. Until a terminology is commonly agreed on, there will be difficulty to design and evaluate a test approach with a general description like structural interaction.

The FIMCAR project worked with two main research activities. One was to develop an evaluation strategy for selecting some combination of suitable test configurations and the second was the technical development activities of specific test candidates. The first activity required terminology, priorities and selection criteria. The second involved crash testing, computer simulation, and data processing to develop the test procedures as well as assessment criteria and performance limits. The remainder of the deliverable will address the evaluation strategy. Adolph et al. [Adolph 2012] summarised all the technical research activities for the test methods. Full documentation of the technical developments for each test configuration are reported in FIMCAR Deliverables D2.2 [Lazaro 2013] (offset test), D3.2 [Adolph 2013/2] (full width test) and D4.2 [Versmissen 2013] (moving deformable barrier test).

2.2 Terminology

From a review of previous research, such as the EEVC WG15 [Faerber 2007], VC-COMPAT project [Edwards 2007], and IHRA [O'Reilly 2003] and additional accident analysis [Seyer 2003], FIMCAR members have established and defined a list of issues that describe the challenges in vehicle crashworthiness. The consortium agreed that:

- compatibility consists of self and partner protection.
- improved compatibility will decrease the injury risks for occupants in single and multiple vehicle accidents.
- compatible vehicles will deform in a stable manner allowing the deformation zones to be exploited even when different vehicle sizes and masses are involved

It is important to separate the physical test process from the assessment of the test results for a test configuration. The assessment of compatibility comes when a combination of test configurations and assessment procedures are used to evaluate vehicle performance. The following definitions were developed within FIMCAR to address technical test developments:

- The *test procedure* specifies the test protocol which includes the barrier face, test speed, overlap etc. That means that the test procedure is also a description of how the test is executed.
- The *assessment procedure* includes the test procedure and the definition of the compatibility metrics. The signal processing requirements and performance criteria are identified.

- The *assessment approach* is then the final combination of the assessment procedures that should evaluate the total safety performance of a vehicle for partner and self protection issues.

In order to address compatibility, a detailed list of compatibility characteristics were identified and prioritised by the consortium. The priorities and test selection approach are presented in the next chapter.

3 FIMCAR ASSESSMENT PROCEDURE SELECTION APPROACH

A frontal impact and compatibility description and prioritisation approach was started early in the FIMCAR project. The issues were divided into 4 main groups: Structural Interaction, Compartment Strength, Frontend Force / Deformation, Deceleration Pulse and Restraint System Assessment. These groupings were further broken down into sub groups to focus the test candidate development. The items listed in Figure 3.1 could be identified in previous research activities. Some of the subtopics could be identified as self protection or partner protection issues and the main idea was to provide a comprehensive description of all frontal impact issues. In brief:

- Structural Interaction describes how the structures of a vehicle deform at the local level when interacting with a collision partner. To achieve good structural interaction there must be some type of *structural alignment* which requires that there are corresponding structures in each collision partner that are geometrically and structurally capable of interacting with the opponents main crash structures. It is preferable that this alignment occurs as early as possible in the crash to maximise the energy absorption and ridedown characteristics for the occupant. As it is not possible to achieve good structural alignment for all possible collision types and collision partners, it is desirable to have good *horizontal and vertical load spreading* so that a robust and stable deformation of all structures can be facilitated.
- Compartment Strength is important to ensure the passenger compartment is free of intrusions and that the frontal energy absorbing structures have a stable reaction base. All vehicles must exhibit good compartment *integrity in single vehicle collisions* such as crashes into objects and HGV. Smaller vehicles have extra risks when colliding with heavier vehicles and one can identify the need for some vehicles to have higher requirements for compartment *integrity for self protection in vehicle-to-vehicle collisions.*
- Front End Force/Deformation Characteristics have two complementary functions depending on the vehicle mass. There is a clear relationship between vehicle deformation forces and vehicle size and there is an interest to control the *deformation forces in frontal structures* when different vehicles collide. Although difficult to guarantee, it is important to not create situations where one vehicle is too stiff and over-crushes a partner vehicle and exploits the energy absorption of the partner vehicle before its own energy absorption processes begins. Similarly it is not desirable to create a vehicle that does not deform in, for example, a single vehicle impact. Insufficient *energy absorption management* will produce vehicles that do not suitably protect an occupant. One can view deformation forces in frontal structures as a means to ensure partner protection and energy absorption management as a self protection issue.
- Deceleration Pulse and Restraint System issues are important parts of a vehicle safety assessment. It is desirable to evaluate the *sensing system for deployable systems* to different crash pulses and deformation patterns to avoid single point optimisation of safety performance. There should also be sufficient *capacity of restraint system* so that an occupant is protected for a high severity impact that could be foreseen. An additional point that is interesting to investigate (but may be difficult to implement as a regulation) is the *evaluation of occupant safety in a partner vehicle.*

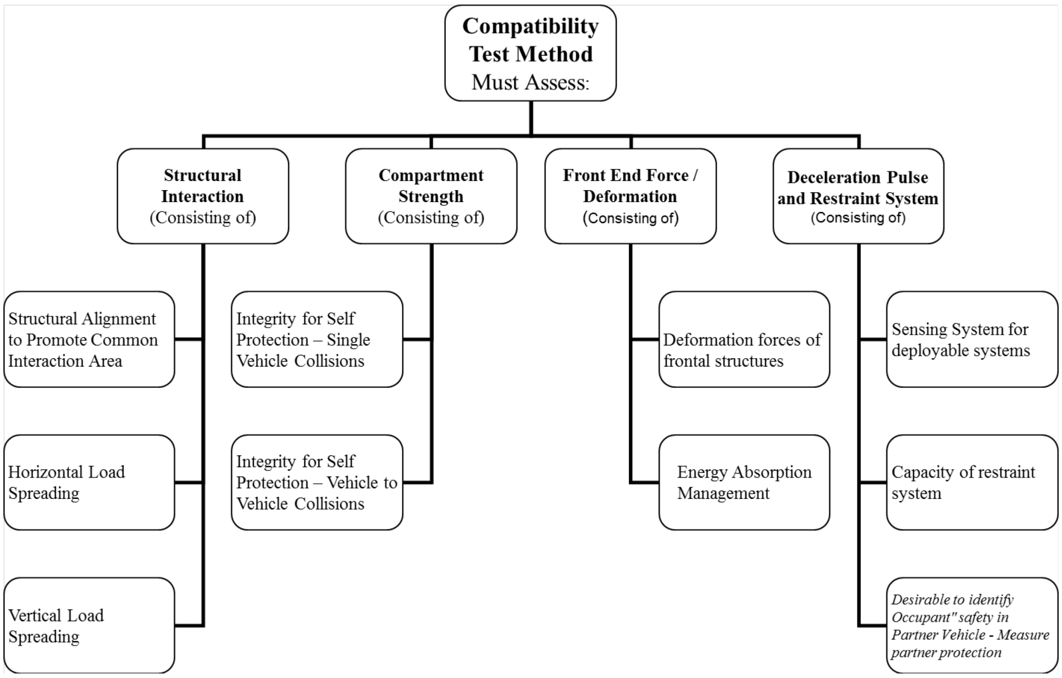

Figure 3.1: Original compatibility characteristics.

3.1 Priorities and Selection Criteria

The main sources for establishing the priorities and selection criteria were the FIMCAR accident analysis analysing frontal impact accidents of UN-ECE Regulation 94 compliant cars (FIMCAR deliverable D1.1 [Thompson 2013]) and the experts present in the FIMCAR meetings. Some of the relevant observations from D1.1 were:

- Poor structural interaction was observed to be a problem in the current vehicle fleet. The dominant structural interaction problems in car-to-car impacts are over/underriding of car fronts and low overlap. However, fork effect is seen more in car-to-object impacts because of impacts with narrow objects.
- In a matched pair analysis of car-to-car impacts, a relationship was found between mass ratio and driver injury severity, namely the higher the mass ratio the higher the driver injury severity (note: mass ratio above 1 means that the partner vehicle is heavier). However, no such relationship was found between mass ratio and compartment strength issues in the limited data available.
- Compartment strength is a particular problem in collisions with HGVs and objects, with these collisions having a high proportion of fatal and MAIS 2+ injuries
- AIS 2+ injuries resulting from deceleration loading of the occupant by the restraint system are present in a significant proportion of frontal crashes, regardless of whether intrusion was present or not.
- High proportion of fatal and MAIS 2+ injuries occur in cases with high overlap (>75%)

The last point reinforced the need for a test condition that requires a vehicle safety system (comprising the frontal structural and occupant restraint system) to withstand a high deceleration, large overlap condition that is not addressed by the current UN-ECE Regulation 94 requirements. Based on the information in Figure 3.1 and D1.1, an updated list of critical compatibility requirements could be developed. In addition, the top level issues described in Figure 3.1 could be reviewed and prioritised in the format shown in Table 1.

Table 1: Main compatibility topics and associated priorities.

	Assessment requirements							
	Structural Interaction		**Front End Force / Deformation (Consisting of)**		**Compartment integrity**		**Restraint system**	
	Alignment	Load Spreading (Load paths / connections)	Deformation forces of frontal structures	Energy Absorption Management	Sufficient for single vehicle accident	Enhanced for light vehicles in vehicle to vehicle accident	(Assess over range of pulses)	Test Restraint Capacity
Priorities For FIMCAR	1	1	2	1	1	2	1	1

Priority 1 items are those that the consortium identified as important for FIMCAR to resolve within the project while Priority 2 items were important but deemed not critical to resolve during the project duration. The most interesting points to note were that the *Deformation forces of frontal structures issues* and issues related to *enhanced compartment strength for light vehicles in vehicle-to-vehicle accident situations* were not a high priority for FIMCAR. This is due to the second bullet point from summary of the FIMCAR accident analysis mentioned above where smaller cars were not found to have a higher risk of intrusion than heavier vehicles. Although this was a conclusion in earlier studies [Faerber 2007], evolution of vehicle safety is resulting in stronger vehicle compartments. As lighter vehicles were not found to have a higher risk of compartment intrusions, even for heavier crash partners, frontal force differences between vehicles were not as critical as perceived earlier. This is a conclusion from a limited dataset and it should be noted that there is still a higher injury risk for small vehicle occupants in car-to-car crashes. Further work is needed to make definitive conclusions but the injury risk for small vehicles seems to now be more related to the higher delta-v a small car experiences rather than its structural capacity.

Project discussions of the accident analysis and compatibility requirements and priorities led to a ranking of priority 1 and priority 2 issues that were evaluated in the project, presented in Table 1.

Table 2: Evaluation criteria and associated priorities.

Priority 1

1 A common interaction zone defined as 406-508 mm (based on US Part 581 zone)
2 Initial Loading of barrier is evaluated above and below 457 mm
3 Vertical Load spreading evaluated in Part 581 zone
4 Vertical Load spreading evaluated between 180 and 406 mm above ground
6 Horizontal load spreading between longitudinal members
8 Current compartment strength requirements maintained
9 Appropriate severity levels for occupant protection
11 Field Relevant pulses in the tests
14 Monitor crash pulses from all test configurations
15 Acceptable Repeatability/Reproducibility performance
16 Appropriate pass/fail thresholds
17 No step effects in metrics
18a) Good cars as rated good
18b) Poor cars as rated poor
19 Detection of vehicle architecture

Priority 2

5 Vertical load spreading above 508 mm
7 Horizontal load spreading beyond longitudinal members
10 Address mass dependent injury risk
12 Two different pulses for restraint system triggering
13 Two different pulses for restraint system capacity

The issues in Table 2 became the basis for evaluating the different full-width and offset test procedures and to see which combination of test and assessment procedures can provide a complete assessment approach for frontal impact and compatibility. The different load cases created in the full-width and offset test configurations facilitates the evaluation of different compatibility characteristics. The potential for each test method is illustrated in Figure 3.2. The benefits and limitations of the different test procedures are apparent and, more importantly, the inability of a single test procedure to fulfil all 15 priority 1 requirements. The main weakness of the offset tests is the ability to assess structural alignment in the beginning of a crash (Item 2) while the full width tests do not suitably assess compartment strength (Item 8).

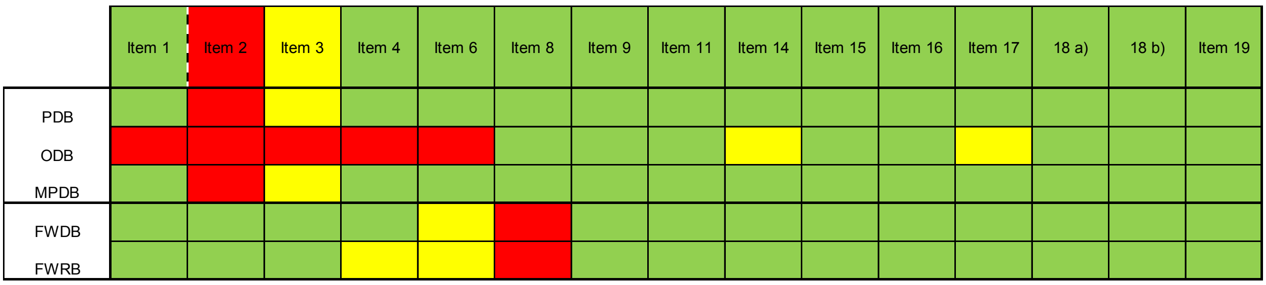

Figure 3.2: Potential of test procedures.

3.2 Evaluation Process

The list of criteria in Table 2 provided a basis for an objective comparison of the test procedures. The technical development of each test and assessment procedure was documented for each of the items. The methods for assessing each criterion varied and were essentially confirmation (yes/no), engineering documentation (data presentation) or assessment with reference vehicles with known properties. The latter case was critical as no single vehicle can be identified as fulfilling all compatibility requirements, but vehicles could be identified with established properties for one or more compatibility characteristic. Lists of physical or numerical vehicle models were developed to document performance in terms of bumper cross beam stiffness, presence of lower load paths, and global performance. Experience in the VC-Compat project [Edwards 2007] suggested that vehicles exhibit a combination of different compatibility characteristics, but specific issues could be isolated in car-to-car tests.

Data from each of the test development work packages in FIMCAR were summarised in a table format based on the items listed in Table 2 but only the Priority 1 issues were addressed in the evaluation conducted in Month 26 of the project. As expected, there was no single test method that could satisfy all the issues and a combination of test procedures was necessary. As a result, the selection of an assessment approach could be separated into two independent evaluations – one for the full width and one for the offset test configurations.

4 RESULTS: FULL WIDTH TEST PROCEDURE

The selection of a full width test procedure was difficult as the 2 candidates each had unique advantages and disadvantages but neither was clearly superior to the other. A list of each test method's advantages were listed in FIMCAR D3.1 [Adolph 2013/1] and are presented in Table 3:

Table 3: Advantages of different full width tests.

FWDB	FWRB
• More representative of real world accident especially in initial stage of impact. • More representative for initial deceleration of vehicle and loading of main rails which is important for sensing of crash for restraint system triggering. • Engine dump loading attenuated, making assessment of vehicle structures that are relevant to crash that are loaded later in the impact, i.e. an assessment can be made of the vehicle's main rails as opposed to its crush cans. • Results in more realistic deformation pattern of the front structure following to shear forces which are not applicable in FWRB • Can detect SEAS structures, so no need for supplementary test, e.g. ORB. • Possibly can assess horizontal structures (bumper beams).	• Effectively already de-facto worldwide standard test so hence would be easier to introduce from harmonisation point of view. • LCW measures vehicle forces directly, i.e. not filtered by deformable element. • No problems with stability of deformable face or possibility of load spreading by deformable face. • More test data available for development of metric

The full width rigid and full width deformable barrier both provide a hard pulse for the occupant and use similar test instrumentation. The main difference is the time window available for assessing vehicle structures. A rigid barrier may only allow a short assessment duration before the engine contacts the load cell wall and begins to mask the structural forces with high contact loads. The deformable barrier face attenuates the engine contact and allows for a longer evaluation period before the engine contact loads mask the structural forces. The technical advantage for assessing structural alignment was for the FWDB while the FWRB offers easier global harmonisation and potentially less test variability due to additional honeycomb materials.

The results of the initial evaluation of the full width procedures are shown in Table 4. The colour coding is used to identify good (green), possible but not confirmed (yellow), not possible (red) and not applicable (blue). Although quite similar, the FWDB had fewer yellow scores than the FWRB and a stronger metric for evaluating the initial structural alignment of main structures. The main weakness of the FWRB was the short time window for analysis.For some vehicles, there was less than 6 ms of data available for assessing the main crash structures. This short time interval would only allow analysis of the bumper and crash boxes but not necessarily the main longitudinals. There appeared to be a risk that vehicles with a bumper that is cantilevered below the longitudinals would be assessed positively even though some evidence suggests this is not a preferred design [Edwards 2007].

Table 4: Evaluation of full width test procedures.

Evaluation Topics *	Description	Full Width Rigid Barrier	Full Width Deformable Barrier
Item 1	Common interaction zone defined as 406-508 mm	Common Interaction zone included in Assessment area 330 mm to 580 mm	Common Interaction zone included in Assessment area 330 mm to 580 mm
Item 2	Initial loading of barrier is evaluated above and below 457 mm	Assessment area evaluates forces above and below 455 mm	Assessment area evaluates forces above and below 455 mm
Item 3	Vertical load spreading evaluated in Part 581	Assessment area evaluates forces above and below 455 mm, criteria for minimum loads above and below centerline	Assessment area evaluates forces above and below 455 mm, criteria for minimum loads above and below centreline
Item 4	Vertical load spreading evaluated between 180 and 406 mm	Additional loads in Row 1&2 can be used in assessment, load path not well detected	Additional loads in Row 1&2 can be used in assessment, load path better detected
Item 6	Horizontal load spreading between longitudinal members	No repeatable metric developed	No repeatable metric developed
Item 8	Current Compartment strength requirements maintained	FW test is an additional test to offset test, not intended for compartment strength	FW test is an additional test to offset test, not intended for compartment strength
Item 9	Appropriate severity level for occupant protection (Delta V)	AIS curves from GIDAS has identified test severity as Delta V 53km/h, proposed test speed 50 km/h	AIS curves from GIDAS has identified test severity as Delta V 53 km/h, proposed initial test speed 50 km/h
Item 11	Field relevant pulse	Overlap greater than 75% second most common impact for fatal and serious injury	Overlap greater than 75% second most common impact for fatal and serious injury
Item 14	Monitor pulses in WP2,3,4	Test data available, ongoing	Test data available, ongoing
Item 15	Repeatability/Reproducibility	Test vehicle selected, testing ongoing, previous data with 2 vehicles, Japanese data available for repeatability	Test vehicle selected, testing ongoing, previous data with 2 vehicles
Item 16	Appropriate pass/fail thresholds	Test thresholds proposed, validation work needed	Test thresholds proposed, validation work needed
Item 17	Check for step effects in metrics	Impact accuracy can control some issues, work ongoing	Impact accuracy can control some issues with load cell size, honeycomb effects should be further evaluated, ongoing
Item 19	Detection of vehicle architecture/loadpaths	Load paths detected in Common Interaction Zone, can assess loads in Row 1&2	Load paths detected in Common Interaction Zone, can potentially assess loads of more rear structures in Row 1&2

The last point in Table 4 was important in the decision to choose a FWRB or a FWDB. The FWRB is able to directly measure the structural loads from the vehicle as there is no honeycomb filtering the forces. However the FWRB could not assess loads in Rows 1&2 as the relevant structures do not load the barrier until later in the impact [Adolph 2013/2].

There has been suggestions to modify the FWRB with an override barrier (ORB) when assessing higher vehicle structures such as SUVs [Patel 2009], but initial FIMCAR data suggests that it may be possible to assess the SEAS that are beneficial for car-to-car collisions by using the FWDB. The GRSP Informal Group on Frontal Impact also advised that additional test requirements were not desirable, even if the test only required for some vehicles.

After the initial evaluation of the test procedures, the consortium selected the full width deformable barrier as the most promising test candidate. There were different metrics available that had exhibited promising results. The outstanding issues that needed to be resolved were the selection and validation of the final assessment metric, criteria for occupant injury, and the test speed. Once this was established, the integration with the offset test was required.

5 RESULTS: OFFSET TEST PROCEDURE

Initial discussions in the FIMCAR project suggested that the existing ODB in UN-ECE Regulation 94 was not capable of evaluating the partner protection characteristics in a vehicle. The PDB and MPDB became the preferred offset test procedures for further development as it was anticipated that a metric for assessing the load spreading capabilities of a vehicle would be developed during the project. There have also been significant discussions on the ability of the PDB to provide a sufficiently severe test condition for all vehicle masses [UNECE 2007].

At the time of the evaluation of the different test candidates, details of the PDB and MPDB testing and simulation activities to assess compatibility characteristics were presented in FIMCAR deliverable D2.1 [Lazaro 2013] and D4.2 [Versmissen 2013]. The results of the offset test candidates are shown in Table 5. There were clear issues with the metrics being developed for the PDB and, at the time of evaluation, no robust metrics were available for the group. The test criteria proposed for assessing load spreading were based on complicated mathematical concepts and involved quantifying iso-curves for barrier deformations. There were discontinuities when the iso-curves crossed the assessment boundaries and this introduced step effects that were not consistent when applied to different vehicles. An additional issue regarding the test severity for heavier vehicles arose for the PDB and, at the time of evaluation, the comparison of test severity for identical vehicles for PDB and ODB tests could not be presented.

Even though the ODB provides no potential for partner protection or load spreading compatibility issues, it was able to maintain the current level of self protection for vehicles. The ODB complemented a FW test in terms of fulfilling the compatibility characteristics that were identified in the project. Unfortunately the lack of a horizontal load spreading criteria in the ODB and FW test resulted in one Priority 1 issue not being fulfilled. Given the time available and the uncertainty to produce a PDB metric, the ODB barrier was chosen as the test method to evaluate self protection and maintain compartment strength in single vehicle collisions. There was no perceived benefit for introducing a new offset test procedure without the guarantee of additional developing an assessment criterion for compatibility within the FIMCAR project. The PDB and MPDB were thus not proposed as the offset test configuration.

Subsequent to the FIMCAR evaluation meeting in Month 28, a supplementary assessment of potential PDB metrics was held. This meeting identified new metrics that were promising for horizontal load spreading but were recognised as not being possible to finalise within the FIMCAR project. Given that the existing ODB criteria would require little if any modification during the FIMCAR project, modest resources were directed to further developing the PDB metric for use by future compatibility researchers after the FIMCAR project.

Table 5: Evaluation of offset tests

Evaluation Topics *	Description	PDB Barrier	ODB	Moving Barrier
Item 1	Common interaction zone defined as 406-508 mm	Common Interaction zone included in a larger assessment area 350-600 mm	No measurement in part 581, bumper element can distort loading	As PDB
Item 2	Initial loading of barrier is evaluated above and below 457 mm	Load path is detected in area above and below 457 mm, specific distribution within zone is not conducted at present, PDB cannot assess initial loading	No measurement in part 581, bumper element can distort loading	As PDB
Item 3	Vertical load spreading evaluated in Part 581	Vertical load spreading is not currently evaluated within part 581 but over larger area (350-600 mm)	No measurement in part 581, bumper element can distort loading	As PDB
Item 4	Vertical load spreading evaluated between 180 and 406 mm	Load path detected in area 180-350 mm using corridors, distribution of load path assessed	Load cell behind honeycomb available, no metric proposed	As PDB
Item 6	Horizontal load spreading between longitudinal members	Horizontal load spreading to be assessed with TV values, results of metric partially confirmed	Bumper element will distort horizontal load spreading	As PDB
Item 8	Current compartment strength requirements maintained	Missing data for heavy vehicles	Current standard	Data presented for MPDB shows suitable levels for smaller vehicles. Heavier vehicles will need a different test severity to maintain current levels
Item 9	Appropriate severity level for occupant protection (Delta V)	N/A	N/A	N/A
Item 11	Field relevant pulse	Offset test configuration addresses most relevant real world case (25-75%)	Offset test configuration addresses most relevant real world case (25-75%)	As PDB
Item 14	Monitor pulses in WP2,3,4	Test data available, ongoing	Limited R94 data available, Euro NCAP available	Test data available, ongoing
Item 15	Repeatability/Reproduci-bility	Earlier test data showed no significant issues. Tests planned to address issue, Need to provide detailed barrier handling and scanning procedures	Repeatable self protection evaluation	As PDB, slightly better results
Item 16	Appropriate pass/fail thresholds	Pass fail approach developed, further validation data needed	Current regulation, chest injury evaluation for women and elderly desirable	Pass fail approach developed, further validation data needed
Item 17	Check for step effects in metrics	Assessment criteria are sensitive to boundaries	Body modifier is yes or no	As PDB
Item 19	Detection of vehicle architecture/loadpaths	Detection of load paths possible with percentile evaluation of deformation	Barrier deformations not possible. Load cell data available	As PDB

6 FINAL DEVELOPMENT OF TEST PROCEDURES

6.1 Full Width Test

After selection of the Full Width Deformable Barrier in the FIMCAR assessment approach, further work was needed to finalise the structural alignment metric, confirm a test speed, report the repeatability and reproducibility results and identify the occupant injury criteria. Due to the fact that none of the final FIMCAR test procedures had a positive assessment for horizontal load spreading, some further research of the FWDB for this purpose was conducted.

FIMCAR Deliverable 3.2 [Adolph 2013/2] documents the final verification of the metric for evaluating the structural alignment of vehicles. The main results and recommendations of the FWDB investigations in the later stages were:

- <u>FWDB test speed of 50 km/h</u>. This meets the desired test severity of a 53 km/h delta-v identified from accident analysis and producing a high pulse [Adolph 2013/2].
- <u>Structural Alignment</u>: The metric to assess structural alignment currently proposes that a vehicle must fulfil minimum load requirements in Rows 3&4 and can use loads in Row 2 to help meet this requirement under certain conditions. The minimum load requirement promotes structural alignment and the credit of loads from Row 2 encourages vertical load spreading. The metric can be defined as:
  - Up to time of 40 ms:
    - $F4 + F3 \geq [MIN(200, 0.4F_{T40}) kN$
    - $F4 \geq [MIN(100, 0.2F_{T40}) kN$
    - $F3 \geq [MIN((100\text{-}LR), (0.2F_{T40}\text{-}LR))]$
    - where:
      - F_{T40} = Maximum of total LCW force up to time of 40 ms
      - Limit Reduction (LR) = [F2-70] kN and 0 kN ≤ LR ≤ 50* kN
      - *Note values to be confirmed taking into account the new test velocity

<u>Horizontal Load Spreading:</u> The FWDB test approach is unable to assess the horizontal load spreading do to the test conditions. The FWDB causes preferential loading through the longitudinals and cannot fully exercise the horizontal links [Adolph 2013/2].

6.2 Off-set Test

The ODB test is proposed as is currently specified in UN-ECE Regulation 94. The current test speed is 56 km/h and no load cell or barrier assessments are proposed. Currently an additional requirement on vehicle intrusions is proposed to ensure all vehicles have a stable occupant compartment. A maximum deformation of 50 mm to the A-pillar is the proposed threshold for this requirement. It is important to note that this requirement will not likely change any of the cars produced for the European market today as Euro NCAP requirements are much more demanding. However, the FIMCAR consortium was reluctant to rely on Euro NCAP assessment for future car homologation and proposes the additional requirement for cars that are probably not designed to give good scores in Euro NCAP as a minimum requirement.

6.3 Occupant Protection Assessment

Due to the scope of the FIMCAR project, requirements for the injury assessment from dummy measurements need to be reviewed by a technical working group after the FIMCAR project is completed and results are consolidated in draft regulations. The accident data reviewed in

FIMCAR suggests that the test dummy type, size, instrumentation, seating location and seat positioning requirements should be reviewed. Female and elderly passengers were identified for better protection. Exploratory tests with a 5th percentile female dummy, instrumented with the RibEye system, seated the front seat passenger position have been conducted to build up a dataset for future modifications to the frontal impact legislation. An initial review of the FIMCAR FWDB dummy injury values for full width deformable barrier (FWDB) tests are compared to current regulatory performance limits in UN-ECE R94 and US FMVSS208 as shown in Table 6.

Table 6: Summary of UN-ECE R94 and US FMVSS208 performance limits.

Criteria	**R94 Limit**	**FMVSS208 Limit**	
	50th %tile	**50th %tile**	**5th %tile**
HIC_{36}	1000	1000	
HIC_{15}		700*	700
Head Resultant Acceleration (3 ms excedence)	80g		
Neck Extension Moment	57 Nm		
Neck tension +Z	Excedence corridor 3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ ≥ 60 ms	4.17 kN	2.620 kN
Neck shear X	Excedence corridor 3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ ≥ 45 ms		
Neck compression –Z		4.00 kN	2.520 kN
N_{ij}		1.0	1.0
Chest Deflection	50 mm	63mm	52 mm
Viscous Criterion	1.00		
Chest acceleration (3 ms excedence)		60g	60g
Femur Compression	9.7 kN	10.0 kN	6.805 kN
Knee Displacement	15 mm		
Tibia Compression	8 kN		
Tibia Index	1.3		

*HIC_{15} used for advanced airbags generally fitted to vehicles 2004+

Further work will be needed to determine the dummy performance limits needed in the Full Width test. The new limits should enforce the incorporation of appropriate restraint systems. The benefit analysis in Deliverable D1.2 [Edwards 2013] assumes that the new FIMCAR assessment approach will deliver the injury reduction assumed by the injury reduction model used in the analysis.

Dummy injury criteria values normalised to the UN-ECE Regulation 94 performance limits for the FWDB tests in the FIMCAR test database are shown for 4 of the most recent model year vehicles in Figure 6.1. All test results shown had a test speed of 56 km/h. Noting that the UN-ECE R94 limits are in general more stringent than the US FMVSS208 ones, the majority of the requirements are met except for 2 exceptions. In order for a prospective full width test to enforce the fitment of improved restraint systems that will deliver the benefit estimated in Deliverable D1.2, it is likely that more stringent performance limits than the current R94 will be needed or indeed perhaps additional tests with different dummy sizes and/or tests at lower speeds with even more stringent performance limits.

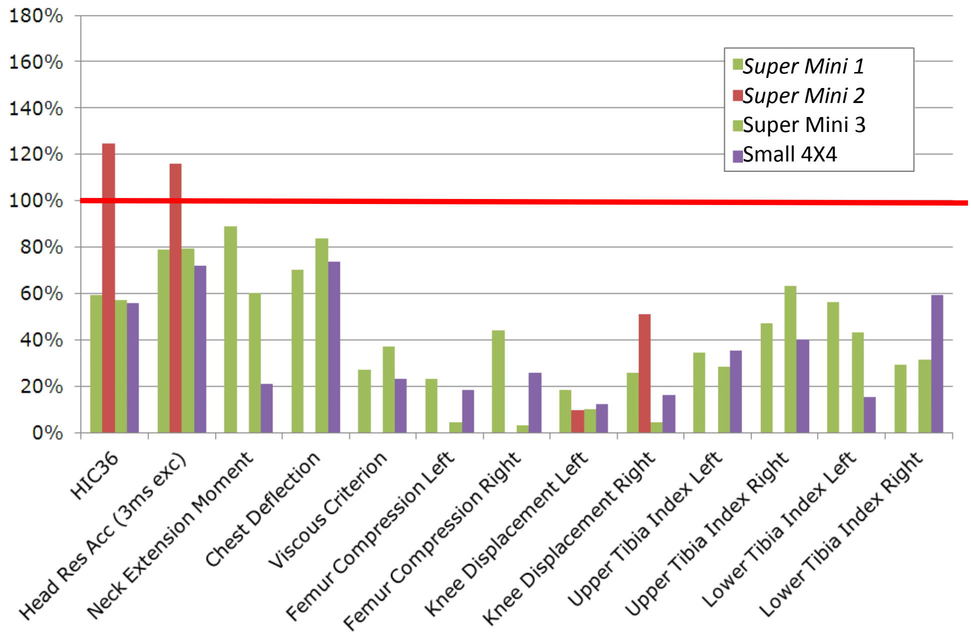

Figure 6.1: Dummy injury criteria values for FWDB tests in FIMCAR test database (late model year cars).

6.4 Conditions for Compliance

Two tests for frontal impact requirements are proposed by FIMCAR and each test configuration must be totally fulfilled, independent of the results of the separate tests.

6.5 Reproducibility and Repeatability

The existing ODB test criteria were not reviewed as the existing regulation test was not subject to this activity. The FWDB was investigated through a combination of component and full scale tests. Component tests were conducted at TRL, BASt, and UTAC and reported in FIMCAR Deliverable D3.2 [Adolph 2013/2]. The component tests showed that the variation of load cell readings was consistent between the tests and below 10%. The component tests also showed no crosstalk or load spreading issues that were critical for the metric.

Full scale tests with a FWDB were reviewed from previous projects (VC-COMPAT [Edwards 2007], APROSYS [Puppini 2007]) and FIMCAR. The earlier projects had limited test data to review - 2 tests with the same vehicle at different test labs. FIMCAR required 3 tests at 2 labs with the same vehicle. The results from the earlier projects showed good correlation for the two test vehicles. The FIMCAR test results were not as consistent. The total loads measured in the three tests were within expected test variation, but the 2 tests at the same research institute had slightly different results which resulted in different evaluation outcomes. The chosen test vehicle had demonstrated instability in car-to-car impacts (FIMCAR D6.1 [Sandqvist 2013]). The Load Cell Wall where the tests were repeated does not meet the instrumentation requirements identified by FIMCAR [Adolph 2013/2] and both of these facts requires further testing to confirm the LCW with deformable barrier is repeatable for the regulation. FIMCAR has concluded that the FWDB Repeatability and Reproducibility is acceptable, in line with other crash tests, for cars with a stable front structure in this test mode. For further analysis of R&R the use of a vehicle exhibiting a stable front structure and total LCW forces above 500 kN is recommended. Furthermore the LCW requirements as developed by FIMCAR shall be met. The test procedure is repeatable within current test

6.6 Worst Case Vehicle Model Selection

During the type approval process, the manufacturer and technical service will determine the appropriate model configuration to be tested. The manufacturer may wish to test a “worst case” example that can be applied to the approval process of related model variants. The selection of the model configuration is subject to negotiation between the manufacturer and the technical service and the FIMCAR cannot recommend any specific conditions that must be tested. The following information is provided for information based on the experience from the research to date.

The proposed assessment approach involves 2 different impact tests presenting different load cases to the vehicle. The worst case configuration in the offset test is not necessarily the worst case for the full width test. FIMCAR recommends that each test condition should be assessed independent of the other.

The ODB test is focused on structural integrity and intrusion driven dummy criteria. The worst case vehicle setup is usually the case with the largest powertrain version and option level that creates the highest intrusions in the occupant compartment.

The FWDB test focusses on acceleration driven dummy criteria and compatibility metrics related to structural alignment. The worst case option for the dummy criteria is the vehicle model with the largest powertrain resulting in a shorter ridedown distance and high compartment accelerations. The compatibility criteria are more difficult to achieve with the smallest powertrain. In this case the vehicle mass is lower and produces less load on the load cell wall.

The use of computer simulation as a method to demonstrate worst case vehicle selection is encouraged. This procedure can be incorporated into the general homologation process as presented in FIMCAR Deliverable D5.5 [Stein 2013].

6.7 Summary Final Development of the Assessment Procedures

FIMCAR has identified a set of test and assessment procedures that can evaluate a vehicle’s frontal impact protection capability. These recommendations will be submitted to rulemaking officials in UN-ECE committees for final evaluation and potential adoption. The current test procedures in the FIMCAR project will potentially introduce new requirements for European vehicles. The introduction of UN-ECE Regulation 94 has eliminated the legislated requirement for a full width test in Europe. Originally, UN-ECE Regulation 12 specified steering wheel intrusion requirements for European vehicles in a FWRB test configuration. However vehicles complying with UN-ECE Regulation 94 will comply with UN-ECE Regulation 12, precluding the need for full width testing of vehicles in Europe.

The FWDB is not a globally harmonised test procedure. As many jurisdictions have the FWRB as a legal requirement, there can be opposition to a test method that is not currently used in any part of the world. Technical advantages for the FWDB have been identified and are documented in Deliverable D3.2 [Adolph 2013/2]. A great deal of attention is being turned to the detection of lower load paths and SEAS as defined in the US voluntary agreement. While no valid test procedure is available for dynamically assessing the lower structures in a vehicle, different studies in the US [Baker 2008, Teoh 2011] have indicated the benefit of the voluntary agreement although the amount of improvement due to the LTV geometry is not conclusive [Greenwall 2012]. Initial evaluations within FIMCAR using simulation, car-to-car testing, and barrier tests indicate that the FWDB may be able to detect the structures relevant for structural alignment and structure interaction without relying on additional tests like the ORB.

The selected offset test procedure, ODB, does not satisfy the load spreading issues identified by the consortium. Subsequent to the initial test candidate selections, work with a horizontal load spreading metric using the FWDB has not succeeded. The FWDB overestimates the loads on longitudinals and does not fully exercise the crossbeam strength of the bumper. This resulted in false evaluations of vehicles that have demonstrated horizontal load spreading properties in car-to-car tests.

As the ODB barrier requires no significant development work, a modest effort was directed to the PDB metrics subsequent even after it was eliminated from the FIMCAR final assessment approach. The PDB and MPDB tests are currently the only configurations that can potentially assess horizontal load spreading. Candidates for assessing load spreading were identified but there is still validation and repeatability issues that must be resolved before the candidates can be forwarded to rule makers. This eliminates them from the final FIMCAR test protocol but not for evaluation after the completion of the project.

7 CONCLUSIONS

The FIMCAR project has made a significant step forward in the assessment of vehicle compatibility. Until this project there were competitive approaches for compatibility assessment available but no clear protocol could be provided by any international research group. FIMCAR has established a prioritised list of evaluation criteria for future frontal impact assessments. This evaluation procedure is developed to the level where specific issues can be addressed without introducing confounding factors in the evaluation process. There is still a lack of appropriate reference vehicles for assessing each performance criteria, but sufficient examples exist to provide objective, technical evaluations of any test or assessment procedure.

Benefit analysis indicates that the introduction of the current FIMCAR assessment approach will increase vehicle safety beyond that which is anticipated through continued vehicle safety developments [Edwards 2013 and van Montfort 2013]. Unfortunately the full potential for improved safety cannot be achieved until an offset test procedure can be developed to assess horizontal and vertical load spreading. New assessment candidates have been identified for the PDB and MPDB and promising results have been obtained to date.

The complete assessment of vehicle frontal impact protection for self and partner protection was confirmed to consist of an offset and a full width test procedure. The combined benefits of assessing loads early in the collision with a full width deformable barrier test, as well as concentrating loads on the vehicle structures with an offset test, address a list of 19 safety issues. The FWDB test at 50 km/h is able to address the high overlap cases that subject occupants to high deceleration loads. These types of injuries are a significant part of the European casualties. The current ODB test at 56 km/h and 40% overlap is a severe load case for the occupant compartment and has resulted in a strengthening of the vehicle structures since its introduction. By maintaining the ODB test, future vehicles should not be able to compromise vehicle self protection which could otherwise be reduced if the requirements in UN-ECE Regulation 94 were to only include those of the FWDB. Both tests enforce designs of vehicles for different, complementary, load cases that are supported by accident data [Thompson 2013].

The 50 km/h FWDB test speed recommended by FIMCAR is based primarily on simulation data. Further testing to confirm the deceleration pulse and assessment criteria, with its reference values, are recommended. Initial repeatability and reproducibility results are promising for the FWDB but need to be repeated using equipment satisfying all the Load Cell Wall instrumentation and specification requirements. The test vehicle should exhibit stable frontal structures to avoid the confounding factors observed in the FIMCAR tests [Adolph 2013/2].

Future activities to evaluate the type of injury risk assessment are encouraged. FIMCAR accident analysis has identified an increased risk of injury to females and elderly vehicle occupants. Different instrumentation and dummy sizes were tested in FIMCAR. The combination of a new, high deceleration, test configuration can be combined with different dummies and injury assessment criteria addressing the more vulnerable car occupants. This will push the development of newer occupant restraint systems that can address a wider range of occupants beyond the 50%ile male.

8 PROPOSED REGULATION FOR FRONTAL IMPACT

1 SCOPE

This Regulation applies to vehicles of category M_1 [1]/ of a total permissible mass not exceeding 2.5 tonnes; other vehicles may be approved at the request of the manufacturer.

2. DEFINITIONS

For the purposes of this Regulation:

2.1. "Protective system" means interior fittings and devices intended to restrain the occupants and contribute towards ensuring compliance with the requirements set out in paragraph 5. below;

2.2. "Type of protective system" means a category of protective devices which do not differ in such essential respects as:

Their technology;
Their geometry;
Their constituent materials;

2.3. "Vehicle width" means the distance between two planes parallel to the longitudinal median plane (of the vehicle) and touching the vehicle on either side of the said plane but excluding the rear-view mirrors, side marker lamps, tyre pressure indicators, direction indicator lamps, position lamps, flexible mud-guards and the deflected part of the tyre side-walls immediately above the point of contact with the ground;

2.4. "Overlap" means the percentage of the vehicle width directly in line with the barrier face;

2.5. "Deformable barrier face" means a crushable section mounted on the front of a rigid block;

2.5.1 "Load Cell Wall" or LCW means the array of force measuring sensors placed on a rigid block

2.6. "Vehicle type" means a category of power-driven vehicles which do not differ in such essential respects as:

2.6.1. The length and width of the vehicle, in so far as they have a negative effect on the results of the impact test prescribed in this Regulation,

2.6.2. The structure, dimensions, lines and materials of the part of the vehicle forward of the transverse plane through the "R" point of the driver's seat, in so far as they have a negative effect on the results of the impact test prescribed in this Regulation,

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[1]/ As defined in Annex 7 to the Consolidated Resolution on the Construction of Vehicles (R.E.3), (TRANS/WP.29/78/Rev.1/Amend.2 as last amended by its Amendment 4).

2.6.3. The lines and inside dimensions of the passenger compartment and the type of protective system, in so far as they have a negative effect on the results of the impact test prescribed in this Regulation,

2.6.4. The siting (front, rear or centre) and the orientation (transversal or longitudinal) of the engine,

2.6.5. The unladen mass, in so far as there is a negative effect on the result of the impact test prescribed in this Regulation,

2.6.6. The optional arrangements or fittings provided by the manufacturer, in so far as they have a negative effect on the result of the impact test prescribed in this Regulation,

2.7. "Passenger compartment" means the space for occupant accommodation, bounded by the roof, floor, side walls, doors, outside glazing and front bulkhead and the plane of the rear compartment bulkhead or the plane of the rear-seat back support;

2.8. "R" point" means a reference point defined for each seat by the manufacturer in relation to the vehicle's structure, as indicated in Annex 6;

2.9. "H" point" means a reference point determined for each seat by the testing service responsible for approval, in accordance with the procedure described in Annex 6;

2.10. "Unladen kerb mass" means the mass of the vehicle in running order, unoccupied and unladen but complete with fuel, coolant, lubricant, tools and a spare wheel (if these are provided as standard equipment by the vehicle manufacturer).

2.11. "Airbag" means a device installed to supplement safety belts and restraint systems in power-driven vehicles, i.e. systems which, in the event of a severe impact affecting the vehicle, automatically deploy a flexible structure intended to limit, by compression of the gas contained within it, the gravity of the contacts of one or more parts of the body of an occupant of the vehicle with the interior of the passenger compartment.

2.12. "Passenger airbag" means an airbag assembly intended to protect occupant(s) in seats other than the driver's in the event of a frontal collision.

2.13. "Child restraint" means an arrangement of components which may comprise a combination of straps or flexible components with a securing buckle, adjusting devices, attachments, and in some cases a supplementary chair and/or an impact shield, capable of being anchored to a power driven vehicle. It is so designed as to diminish the risk of injury to the wearer, in the event of a collision or of abrupt deceleration of the vehicle by limiting the mobility of the wearer's body.

2.14. "Rearward-facing" means facing in the direction opposite to the normal direction of travel of the vehicle.

3. APPLICATION FOR APPROVAL

As documented in current R94

4. APPROVAL

As documented in current R94

5. SPECIFICATIONS

5.1. <u>General specifications applicable to all tests</u>

The following specifications apply to all tests described in Annexes 3a and 3b.

5.1.1. The "H" point for each seat shall be determined in accordance with the procedure described in Annex 6.

5.1.2. When the protective system for the front seating positions includes belts, the belt components shall meet the requirements of Regulation No. 16.

5.1.3. Seating positions where a dummy is installed and the protective system includes belts, shall be provided with anchorage points conforming to Regulation No. 14.

5.2. <u>Specifications</u>

Full Width Deformable Tests of the vehicle carried out in accordance with the method described in Annex 3a shall be considered satisfactory if all the conditions set out in paragraphs 5.2.1a.and 5.2.2 to 5.2.6. below are all satisfied at the same time.

Offset Deformable Tests of the vehicle carried out in accordance with the method described in Annex 3b shall be considered satisfactory if all the conditions set out in paragraphs 5.2.1b.and 5.2.2 to 5.2.6. below are all satisfied at the same time.

All specifications prescribed under 5.2 must be fulfilled at the same time.

5.2.1.a Full Width Test

5.2.1.a.1 The performance criteria recorded, in accordance with Annex 8.a, on the dummies in the front outboard seats shall meet the following conditions:

Note: Annex 8.a to be updated by GRSP Dummy Expert working group for the Full Width Deformable Barrier. Relevant Performance Criteria will then be defined in this section

5.2.1.a.2 The vehicles structural performance criteria recorded, in accordance to the method described in Annex 11, shall comply to one of the following conditions

5.2.1.a.2.1 Condition 1

- $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
- $F4 \geq [MIN(100, 0.2F_{T40})$ kN
- $F3 \geq [MIN((100), (0.2F_{T40}))]$

5.2.1.a.2.2 Condition 2

- $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
- $F4 \geq [MIN(100, 0.2F_{T40})$ kN
- $F3 \geq [MIN((100-LR), (0.2F_{T40}-LR))]$ but not less than 70] kN

– where:

- Limit Reduction (LR) = [MIN([F2-70], 30)] kN

5.2.1.b Offset Test

5.2.1.b.1 The performance criteria recorded, in accordance with Annex 8.b, on the dummies in the front outboard seats shall meet the following conditions:

Note: Annex 8.b is currently proposed to be the existing Annex 8 in R94 unless updated by GRSP Dummy Expert working. Relevant Performance Criteria will then be defined in this section

5.2.1.b.2 The vehicles structural performance criteria recorded, in accordance to the method described in Annex 12, shall comply to one of the following conditions

5.2.1.b.2.1 The A-Pillar intrusions described in Annex 12 shall not exceed 50 mm.

5.2.2. Residual steering wheel displacement, measured at the centre of the steering wheel hub, shall not exceed 80 mm in the upwards vertical direction and 100 mm in the rearward horizontal direction.

5.2.3. During the test no door shall open.

5.2.4. During the test no locking of the locking systems of the front doors shall occur.

5.2.5. After the impact, it shall be possible, without the use of tools, except for those necessary to support the weight of the dummy:

5.2.5.1. To open at least one door, if there is one, per row of seats and, where there is no such door, to move the seats or tilt their backrests as necessary to allow the evacuation of all the occupants; this is, however, only applicable to vehicles having a roof of rigid construction;

5.2.5.2 To release the dummies from their restraint system which, if locked, shall be capable of being released by a maximum force of 60 N on the centre of the release control;

5.2.5.3. To remove the dummies from the vehicle without adjustment of the seats.

5.2.6. In the case of a vehicle propelled by liquid fuel, no more than slight leakage of liquid from the fuel feed installation shall occur on collision.

5.2.7. If there is continuous leakage of liquid from the fuel-feed installation after the collision, the rate of leakage shall not exceed 30 g/min; if the liquid from the fuel-feed system mixes with liquids from the other systems and the various liquids cannot easily be separated and identified, all the liquids collected shall be taken into account in evaluating the continuous leakage.

6. Instructions for users of vehicles equipped with airbags

Unchanged from existing R94

7. MODIFICATION AND EXTENSION OF APPROVAL OF THE VEHICLE TYPE

Unchanged from existing R94

8. CONFORMITY OF PRODUCTION

Unchanged from existing R94

9. PENALTIES FOR NON-CONFORMITY OF PRODUCTION

Unchanged from existing R94

10. PRODUCTION DEFINITELY DISCONTINUED

Unchanged from existing R94

11. TRANSITIONAL PROVISIONS

To be defined by GRSP

12. NAMES AND ADDRESSES OF TECHNICAL SERVICES RESPONSIBLE FOR CONDUCTING APPROVAL TESTS, AND OF ADMINISTRATIVE DEPARTMENTS

Unchanged from existing R94

Annex 1 – COMMUNICATION

As specified in current regulation

Annex 2 -ARRANGEMENTS OF THE APPROVAL MARK

As specified in current regulation – only significant issue is if “94” is appropriate

Annex 3a Full Width TEST PROCEDURE

1. INSTALLATION AND PREPARATION OF THE VEHICLE

1.1. Testing ground

The test area shall be large enough to accommodate the run-up track, barrier and technical installations necessary for the test. The last part of the track, for at least 5 m before the barrier, shall be horizontal, flat and smooth.

1.2. Barrier

1.2.1 Rigid Block

Fixtures related to barrier faces and instrumentation shall be mounted on a fixed rigid barrier. The barrier has a mass of not less than 7 x 10^4 kg, the front face of which is vertical within ± 1°. The mass is anchored in the ground or placed on the ground with, if necessary, additional arresting devices to restrict its movement.

1.2.2 Load cell wall (LCW)

The rigid block will be fitted with a load cell wall. The load cell wall is to be formed by a matrix of individual load cells with a spacing of 125mm in the horizontal and vertical directions. The width of the load cell wall is to be equal to or greater than the width of the deformable barrier and to be exactly divisible by 250mm. The height is to be equal to or greater than the height of the deformable element. [Width 2000mm, height 1000mm]. The lower edge of the load cell wall shall be 80 mm above the ground surface. Specifications for the load cell elements and construction accuracy are given in Annex 11.

1.2.3 Deformable Element

The front face of the barrier will be fitted by a deformable structures specified in Annex 9a.

1.3. Alignment of deformable element

The lower edge of the deformable element, excluding the mounting flanges, is to be aligned with the lower edge of the load cell wall. The vertical centreline of the deformable element is to be aligned with the vertical centre line of the load cell wall. In order to attach the deformable element to the load cell wall, the MDF facings on the lower row of load cells are to extend below the lower edge of the load cells. The barrier is fixed to the load cell wall by means of a clamping plate along the upper edge and along the lower edge. The bolts used to attach the clamping plate must not pass through the mounting flange.

[If the impact area of the test vehicle were likely to exceed the upper edge of the deformable element when at the minimum height of 1000mm, an alternative option to increasing the height of the deformable element would be to increase the height of the LCW relative to the ground. This is provided that the lower edge of the impact area is a minimum of 125mm further from the ground level in the vertical direction than the lower edge of the deformable element when in the new position.

The proposed increase in height would be in 125mm steps beginning at 80mm relative to the ground.]

1.3.1 Alignment of vehicle to barrier

The fore/aft centre line of the vehicle is to be aligned with the vertical centre line of the deformable element facing the barrier. The vertical alignment of the vehicle is to be recorded prior to the test. The measurement is the vertical distance between the wheel to ground contact for each wheel and the wheel arch immediately above the contact patch. Prior to measurement the vehicle will be at test mass and rolled back and forward at least one vehicle length to settle the vehicle.

1.4. State of vehicle

1.4.1. General specification

The test vehicle shall be representative of the series production, shall include all the equipment normally fitted and shall be in normal running order. Some components may be replaced by equivalent masses where this substitution clearly has no noticeable effect on the results measured under paragraph 6.

1.4.2. Mass of vehicle

1.4.2.1. For the test, the mass of the vehicle submitted shall be the unladen kerb mass;

1.4.2.2. The fuel tank shall be filled with water to mass equal to 90 per cent of the mass of a full as specified by the manufacturer with a tolerance of $\pm$ 1 per cent;

1.4.2.3. All the other systems (brake, cooling, ...) may be empty in this case, the mass of the liquids shall be carefully compensated;

1.4.2.4. If the mass of the measuring apparatus on board the vehicle exceeds the 25 kg allowed, it may be compensated by reductions which have no noticeable effect on the results measured under paragraph 6. below.

1.4.2.5. The mass of the measuring apparatus shall not change each axle reference load by more than 5 per cent, each variation not exceeding 20 kg.

1.4.2.6. The mass of the vehicle resulting from the provisions of paragraph 1.4.2.1. above shall be indicated in the report.

1.4.3. Passenger compartment adjustments

1.4.3.1. Position of steering wheel

The steering wheel, if adjustable, shall be placed in the normal position indicated by the manufacturer or, failing that, midway between the limits of its range(s) of adjustment. At the end of propelled travel, the steering wheel shall be left free, with its spokes in the position which according to the manufacturer corresponds to straight-ahead travel of the vehicle.

1.4.3.2. Glazing

The movable glazing of the vehicle shall be in the closed position. For test measurement purposes and in agreement with the manufacturer, it may be lowered, provided that the position of the operating handle corresponds to the closed position.

1.4.3.3. Gear-change lever

The gear-change lever shall be in the neutral position.

1.4.3.4. Pedals

The pedals shall be in their normal position of rest. If adjustable, they shall be set in their mid position unless another position is specified by the manufacturer.

1.4.3.5. Doors

The doors shall be closed but not locked.

1.4.3.6. Opening roof

If an opening or removable roof is fitted, it shall be in place and in the closed position. For test measurement purposes and in agreement with the manufacturer, it may be open.

1.4.3.7. Sun-visor

The sun-visors shall be in the stowed position.

1.4.3.8. Rear-view mirror

The interior rear-view mirror shall be in the normal position of use.

1.4.3.9. Arm-rests

Arm-rests at the front and rear, if movable, shall be in the lowered position, unless this is prevented by the position of the dummies in the vehicles.

1.4.3.10. Head restraints

Head restraints adjustable for height shall be in their uppermost position.

1.4.3.11. Seats

1.4.3.11.1. Position of front seats

Seats adjustable longitudinally shall be placed so that their "H" point, determined in accordance with the procedure set out in Annex 6 is in the middle position of travel or in the nearest locking position thereto, and at the height position defined by the manufacturer (if independently adjustable for height). In the case of a bench seat, the reference shall be to the "H" point of the driver's place.

1.4.3.11.2. Position of the front seat-backs

If adjustable, the seat-backs shall be adjusted so that the resulting inclination of the torso of the dummy is as close as possible to that recommended by the manufacturer for normal use or, in the absence of any particular recommendation by the manufacturer, to 25° towards the rear from the vertical.

1.4.3.11.3. Rear seats

If adjustable, the rear seats or rear bench seats shall be placed in the rearmost position.

2. DUMMIES

2.1. Front seats

The dummy size, seating, and positioning requirements should be reviewed by the GRSP dummy expert group

2.1.1. A dummy corresponding to the specifications for Hybrid III [2]/ fitted with a 45° ankle and meeting the specifications for its adjustment shall be installed in each of the front outboard seats in accordance with the conditions set out in Annex 5. The dummy shall be equipped for recording the data necessary to determine the performance criteria with measuring systems corresponding to the specifications in Annex 8. The ankle of the dummy shall be certified in accordance with the procedures in Annex 10.

2.1.2. The car will be tested with restraint systems, as provided by the manufacturer.

3. Propulsion and course of vehicle

1 3.1. The vehicle shall be propelled either by its own engine or by any other propelling device.

3.2. At the moment of impact the vehicle shall no longer be subject to the action of any additional steering or propelling device.

3.3. The course of the vehicle shall be such that it satisfies the requirements of paragraphs 1.2. and 1.3.1.

4. TEST SPEED

4.1 Vehicle speed at the moment of impact shall be 50 -0/+1 km/h. However, if the test was performed at a higher impact speed and the vehicle met the requirements, the test shall be considered satisfactory.

5. MEASUREMENTS TO BE MADE ON DUMMY IN FRONT SEATS

5.1. All the measurements necessary for the verification of the performance criteria shall be made with measurement systems corresponding to the specifications of Annex 8.

5.2. The different parameters shall be recorded through independent data channels of the following CFC (Channel Frequency Class):

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[2]/ The technical specifications and detailed drawings of Hybrid III, corresponding to the principal dimensions of a fiftieth percentile male of the United States of America, and the specifications for its adjustment for this test are deposited with the Secretary-General of the United Nations and may be consulted on request at the secretariat of the Economic Commission for Europe, Palais des Nations, Geneva, Switzerland.

5.2.1. Measurements in the head of the dummy

The acceleration (a) referring to the centre of gravity is calculated from the triaxial components of the acceleration measured with a CFC of 1000.

5.2.2. Measurements in the neck of the dummy

5.2.2.1. The axial tensile force and the fore/aft shear force at the neck/head interface are measured with a CFC of 1000.

5.2.2.2. The bending moment about a lateral axis at the neck/head interface are measured with a CFC of 600.

5.2.3. Measurements in the thorax of the dummy

The chest deflection between the sternum and the spine is measured with a CFC of 180.

5.2.4. Measurements in the femur and tibia of the dummy

5.2.4.1. The axial compressive force and the bending moments are measured with a CFC of 600.

5.2.4.2. The displacement of the tibia with respect to the femur is measured at the knee sliding joint with a CFC of 180.

6. MEASUREMENTS TO BE MADE ON THE VEHICLE

6.1. To enable the simplified test described in Annex 7 to be carried out, the deceleration time history of the structure shall be determined on the basis of the value of the longitudinal accelerometers at the base of the "B" pillar on both sides of the vehicle with a CFC of 180 by means of data channels corresponding to the requirements set out in Annex 8;

6.2. The speed time history which will be used in the test procedure described in Annex 7 shall be obtained from average of the longitudinal accelerometers at the "B" pillars on both sides of the vehicle.

Annex 3b OFFSET TEST PROCEDURE

1. INSTALLATION AND PREPARATION OF THE VEHICLE

1.1. Testing ground

The test area shall be large enough to accommodate the run-up track, barrier and technical installations necessary for the test. The last part of the track, for at least 5 m before the barrier, shall be horizontal, flat and smooth.

1.2. Barrier

1.2.1 Rigid Block

Fixtures related to barrier faces and instrumentation shall be mounted on a fixed rigid barrier. The barrier has a mass of not less than 7 x 10^4 kg, the front face of which is vertical within ± 1°. The mass is anchored in the ground or placed on the ground with, if necessary, additional arresting devices to restrict its movement.

1.2.2 Offset Deformable Test

Based on 1.2.1, the following conditions apply to the Offset test:

1.3 Orientation of the barrier

The orientation of the barrier is such that the first contact of the vehicle with the barrier is on the steering-column side. Where there is a choice between carrying out the test with a right-hand or left-hand drive vehicle, the test shall be carried out with the less favourable hand of drive as determined by the Technical Service responsible for the tests.

1.3.1. Alignment of the vehicle to the barrier

The vehicle shall overlap the barrier face by 40 per cent ± 20 mm.

1.4. State of vehicle

1.4.1. General specification

The test vehicle shall be representative of the series production, shall include all the equipment normally fitted and shall be in normal running order. Some components may be replaced by equivalent masses where this substitution clearly has no noticeable effect on the results measured under paragraph 6.

1.4.2. Mass of vehicle

1.4.2.1. For the test, the mass of the vehicle submitted shall be the unladen kerb mass;

1.4.2.2. The fuel tank shall be filled with water to mass equal to 90 per cent of the mass of a full as specified by the manufacturer with a tolerance of ± 1 per cent;

1.4.2.3. All the other systems (brake, cooling, ...) may be empty in this case, the mass of the liquids shall be carefully compensated;

1.4.2.4. If the mass of the measuring apparatus on board the vehicle exceeds the 25 kg allowed, it may be compensated by reductions which have no noticeable effect on the results measured under paragraph 6. below.

1.4.2.5. The mass of the measuring apparatus shall not change each axle reference load by more than 5 per cent, each variation not exceeding 20 kg.

1.4.2.6. The mass of the vehicle resulting from the provisions of paragraph 1.4.2.1. above shall be indicated in the report.

1.4.3. Passenger compartment adjustments

1.4.3.1. Position of steering wheel

The steering wheel, if adjustable, shall be placed in the normal position indicated by the manufacturer or, failing that, midway between the limits of its range(s) of adjustment. At the end of propelled travel, the steering wheel shall be left free, with its spokes in the position which according to the manufacturer corresponds to straight-ahead travel of the vehicle.

1.4.3.2. Glazing

The movable glazing of the vehicle shall be in the closed position. For test measurement purposes and in agreement with the manufacturer, it may be lowered, provided that the position of the operating handle corresponds to the closed position.

1.4.3.3. Gear-change lever

The gear-change lever shall be in the neutral position.

1.4.3.4. Pedals

The pedals shall be in their normal position of rest. If adjustable, they shall be set in their mid position unless another position is specified by the manufacturer.

1.4.3.5. Doors

The doors shall be closed but not locked.

1.4.3.6. Opening roof

If an opening or removable roof is fitted, it shall be in place and in the closed position. For test measurement purposes and in agreement with the manufacturer, it may be open.

1.4.3.7. Sun-visor

The sun-visors shall be in the stowed position.

1.4.3.8. Rear-view mirror

The interior rear-view mirror shall be in the normal position of use.

1.4.3.9. Arm-rests

Arm-rests at the front and rear, if movable, shall be in the lowered position, unless this is prevented by the position of the dummies in the vehicles.

1.4.3.10. Head restraints

Head restraints adjustable for height shall be in their uppermost position.

1.4.3.11. Seats

1.4.3.11.1. Position of front seats

Seats adjustable longitudinally shall be placed so that their "H" point, determined in accordance with the procedure set out in Annex 6 is in the middle position of travel or in the nearest locking position thereto, and at the height position defined by the manufacturer (if independently adjustable for height). In the case of a bench seat, the reference shall be to the "H" point of the driver's place.

1.4.3.11.2. Position of the front seat-backs

If adjustable, the seat-backs shall be adjusted so that the resulting inclination of the torso of the dummy is as close as possible to that recommended by the manufacturer for normal use or, in the absence of any particular recommendation by the manufacturer, to 25° towards the rear from the vertical.

1.4.3.11.3. Rear seats

If adjustable, the rear seats or rear bench seats shall be placed in the rearmost position.

2. DUMMIES

2.1. Front seats

The dummy size, seating, and positioning requirements should be reviewed by the GRSP dummy expert group

2.1.1. A dummy corresponding to the specifications for Hybrid III [3]/ fitted with a 45° ankle and meeting the specifications for its adjustment shall be installed in each of the front outboard seats in accordance with the conditions set out in Annex 5. The dummy shall be equipped for recording the data necessary to determine the performance criteria with measuring systems corresponding to the specifications in Annex 8. The ankle of the dummy shall be certified in accordance with the procedures in Annex 10.

2.1.2. The car will be tested with restraint systems, as provided by the manufacturer.

3. Propulsion and course of vehicle

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[3]/ The technical specifications and detailed drawings of Hybrid III, corresponding to the principal dimensions of a fiftieth percentile male of the United States of America, and the specifications for its adjustment for this test are deposited with the Secretary-General of the United Nations and may be consulted on request at the secretariat of the Economic Commission for Europe, Palais des Nations, Geneva, Switzerland.

3.1. The vehicle shall be propelled either by its own engine or by any other propelling device.

3.2. At the moment of impact the vehicle shall no longer be subject to the action of any additional steering or propelling device.

3.3. The course of the vehicle shall be such that it satisfies the requirements of paragraphs 1.2. and 1.3.1.

4. TEST SPEED

4.1 Offset Test

Vehicle speed at the moment of impact shall be 56 -0/+1 km/h. However, if the test was performed at a higher impact speed and the vehicle met the requirements, the test shall be considered satisfactory.

5. MEASUREMENTS TO BE MADE ON DUMMY IN FRONT SEATS

5.1. All the measurements necessary for the verification of the performance criteria shall be made with measurement systems corresponding to the specifications of Annex 8.

5.2. The different parameters shall be recorded through independent data channels of the following CFC (Channel Frequency Class):

5.2.1. <u>Measurements in the head of the dummy</u>

The acceleration (a) referring to the centre of gravity is calculated from the triaxial components of the acceleration measured with a CFC of 1000.

5.2.2. <u>Measurements in the neck of the dummy</u>

5.2.2.1. The axial tensile force and the fore/aft shear force at the neck/head interface are measured with a CFC of 1000.

5.2.2.2. The bending moment about a lateral axis at the neck/head interface are measured with a CFC of 600.

5.2.3. <u>Measurements in the thorax of the dummy</u>

The chest deflection between the sternum and the spine is measured with a CFC of 180.

5.2.4. <u>Measurements in the femur and tibia of the dummy</u>

5.2.4.1. The axial compressive force and the bending moments are measured with a CFC of 600.

5.2.4.2. The displacement of the tibia with respect to the femur is measured at the knee sliding joint with a CFC of 180.

6. MEASUREMENTS TO BE MADE ON THE VEHICLE

6.1. To enable the simplified test described in Annex 7 to be carried out, the deceleration time history of the structure shall be determined on the basis of the value of the longitudinal accelerometers at the base of the "B" pillar on the struck side of the vehicle with a CFC of 180 by means of data channels corresponding to the requirements set out in Annex 8;

6.2. The speed time history which will be used in the test procedure described in Annex 7 shall be obtained from the longitudinal accelerometer at the "B" pillar on the struck side.

6.3 Intrusion measurements of the A-pillar shall be conducted in accordance to Appendix 12

ANNEXES 4-8 SHOULD BE REVIEWED BY GRSP

Annex 9a DEFINITION OF FULL WIDTH DEFORMABLE BARRIERS

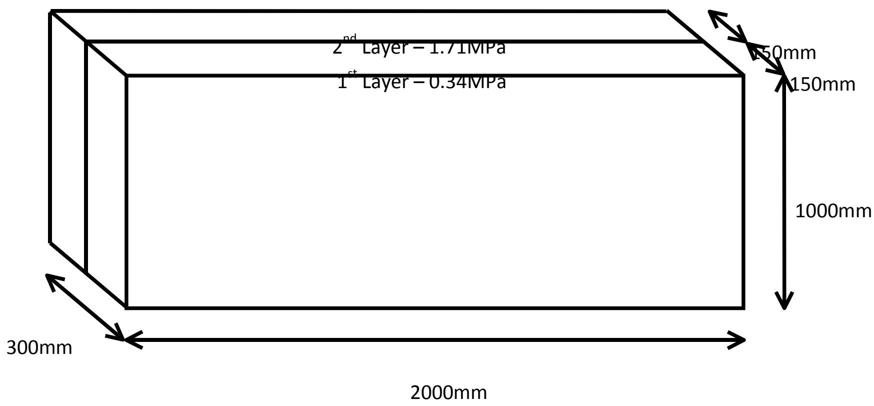
1. COMPONENT AND MATERIAL SPECIFICATIONS

Main honeycomb block

The external dimensions of the barrier are illustrated in Figure 1. The deformable element is formed from two layers of aluminium honeycomb, with an overall depth of 300mm, a height of 1000mm and a width of 2000mm. [For larger vehicles the height and the width of the deformable element should be increased in 125mm increments vertically and 250mm increments horizontally to ensure that no part of the vehicle directly impacts the LCW.]

Figure 1

Full Width Deformable Barrier external dimensions (not to scale).



1.1 Front honeycomb layer

Height: 1000 mm (in direction of honeycomb ribbon axis)

Width: 2000 mm

Depth: 150 mm (in direction of honeycomb cell axes)

Material: Aluminium 3003 (ISO 209, part 1)

Foil thickness: 0.076 mm

Cell size: 19.14 mm

Density: 28.6 kg/m3

Crush strength: 0.342 MPa +0% -10%

1.2 Rear honeycomb layer

Height: 1000mm [□ 2.5mm] (in direction

Width: 2000mm [□ 2.5mm]

Depth: 150mm [□ 1mm] (in direction of hon

Material: Aluminium 3003 (ISO 209, part 1)

Foil thickness: 0.076 mm

Cell size: 6.4 mm

Density: 82.6 kg/ m3

Crush strength: 1.711 MPa +0% -10%

1.3 Backing sheet

Height: 1080 mm □ 2.5 mm

Width: 2000 mm □ 2.5 mm

Thickness: 0.5 mm □ 0.1 mm

Material: Aluminium 5251

1.4 The adhesive to be used throughout should be a two-part polyurethane (such as Ciba-Geigy XB5090/1 resin with XB5304 hardener, or equivalent).

2. ALUMINIUM HONEYCOMB CERTIFICATION

A complete testing procedure for certification of aluminium honeycomb is given in NHTSA TP-214D. The following is a summary of the procedure that should be applied to materials for the frontal impact barrier, these materials having a crush strength of 0.342 MPa and 1.711 MPa respectively.

2.1. Sample locations

To ensure uniformity of crush strength across the whole of the barrier face, eight samples shall be taken from four locations evenly spaced across the honeycomb block. For a block to pass certification, seven of these eight samples shall meet the crush strength requirements of the following sections.

The location of the samples depends on the size of the honeycomb block. First, four samples, each measuring 300 mm x 300 mm x 50 mm thick shall be cut from the block of barrier face material. Please refer to Figure 2 for an illustration of how to locate these sections within the honeycomb block. Each of these larger samples shall be cut into samples for certification testing (150 mm x 150 mm x 50 mm). Certification shall be based on the testing of two samples from each of these four locations. The other two should be made available to the applicant, upon request.

2.2. Sample size

Samples of the following size shall be used for testing:

Length: 150 mm ± 6 mm

Width: 150 mm ± 6 mm

Thickness: 50 mm ± 2 mm

The walls of incomplete cells around the edge of the sample shall be trimmed as follows:

In the "W" direction, the fringes shall be no greater than 1.8 mm (see Figure 3).

In the "L" direction, half the length of one bonded cell wall (in the ribbon direction) shall be left at either end of the specimen (see Figure 3).

2.3. Area measurement

The length of the sample shall be measured in three locations, 12.7 mm from each end and in the middle, and recorded as L1, L2 and L3 (Figure 3). In the same manner, the width shall be measured and recorded as W1, W2 and W3 (Figure 3). These measurements shall be taken on the centreline of the thickness. The crush area shall then be calculated as:

$$A = \frac{(L1 + L2 + L3)}{3} \text{ x } \frac{(W1 + W2 + W3)}{3}$$

2.4. Crush rate and distance

The sample shall be crushed at a rate of not less than 5.1 mm/min and not more than 7.6 mm/min. The minimum crush distance shall be 16.5 mm.

2.5. Data collection

Force versus deflection data are to be collected in either analog or digital form for each sample tested. If analog data are collected then a means of converting this to digital shall be available. All digital data shall be collected at a rate of not less than 5 Hz (5 points per second).

2.6. Crush strength determination

Ignore all data prior to 6.4 mm of crush and after 16.5 mm of crush. Divide the remaining data into three sections or displacement intervals (n = 1, 2, 3) (see Figure 4) as follows:

(1) 06.4 mm - 09.7 mm inclusive,

(2) 09.7 mm - 13.2 mm exclusive,

(3) 13.2 mm - 16.5 mm inclusive.

Find the average for each section as follows:

$$F(n) = \frac{(F(n)1 + F(n)2 + ... + F(n)m)}{m}; \quad m = 1, 2, 3$$

where m represents the number of data points measured in each of the three intervals. Calculate the crush strength of each section as follows:

$$S(n) = \frac{F(n)}{A}; \quad n = 1, 2, 3$$

2.7. Sample crush strength specification

For a honeycomb sample to pass this certification, the following conditions shall be met:

0.308 MPa ≤ S(n) ≤ 0.342 MPa for 0.342 MPa material

1.540 MPa ≤ S(n) ≤ 1.711 MPa for 1.711 MPa material

n = 1, 2, 3.

2.8. Block crush strength specification

Eight samples are to be tested from four locations, evenly spaced across the block. For a block to pass certification, seven of the eight samples shall meet the crush strength specification of the previous section.

3. ADHESIVE BONDING PROCEDURE

3.1. Immediately before bonding, aluminium sheet surfaces to be bonded shall be thoroughly cleaned using a suitable solvent, such as 1-1-1 Trichloroethane. This is to be carried out at least twice or as required to eliminate grease or dirt deposits. The cleaned surfaces shall then be abraded using 120 grit abrasive paper. Metallic/Silicon Carbide abrasive paper is not to be used. The surfaces shall be thoroughly abraded and the abrasive paper changed regularly during the process to avoid clogging, which may lead to a polishing effect. Following abrading, the surfaces shall be thoroughly cleaned again, as above. In total, the surfaces shall be solvent cleaned at least four times. All dust and deposits left as a result of the abrading process shall be removed, as these will adversely affect bonding.

3.2. The adhesive should be applied to one surface only, using a ribbed rubber roller. In cases where honeycomb is to be bonded to aluminium sheet, the adhesive should be applied to the aluminium sheet only.

A maximum of 0.5 kg/m^2 shall be applied evenly over the surface, giving a maximum film thickness of 0.5 mm.

4. CONSTRUCTION

4.1. The rear honeycomb layer is segmented every 125mm in the horizontal and vertical directions starting at 125mm from the outer edges. The position of each of the segmentation slots is to be measured from the outer edge of the barrier to prevent compound errors. [The slot size is to be less than 5mm wide.]

4.2. The rear honeycomb layer shall be bonded to the backing sheet with adhesive such that the cell axes are perpendicular to the sheet.

4.3. The front honeycomb layer shall be adhesively bonded to the rear honeycomb layer by means of a muslin interlayer sheet, such that the cell axes are perpendicular to the sheet. The deformable element is formed from two layers of aluminium honeycomb, with an overall depth of 300mm, a minimum height and width of 1000mm and 2000mm respectively. [For larger vehicles the height and the width of the deformable element should be increased in 125mm increments vertically and 250mm increments horizontally to ensure that no part of the vehicle directly impacts the LCW.]

5. MOUNTING

5.1. The deformable barrier shall be rigidly fixed to the edge of a mass of not less than 7 x 10^4 kg or to some structure attached thereto. The attachment of the barrier face shall be such that the vehicle shall not contact any part of the structure more than 75 mm from the top surface of the barrier (excluding the upper flange) during any stage of the impact[1]. The front face of the surface to which the deformable barrier is attached shall be flat and continuous over the height and width of the face and shall be vertical ± 1° and perpendicular ± 1° to the axis of the run-up track. The attachment surface shall not be displaced by more than 10 mm during the test. If necessary, additional anchorage or arresting devices shall be used to prevent displacement of the concrete block. The edge of the deformable barrier shall be aligned with the edge of the concrete block appropriate for the side of the vehicle to be tested.

5.2. Deformable Barrier Face Mounting

The lower edge of the deformable element, excluding the mounting flanges, is to be aligned with the lower edge of the load cell wall. The vertical centreline of the deformable element is to be aligned with the vertical centre line of the load cell wall. In order to attach the deformable element to the load cell wall, the MDF facings on the lower row of load cells are to extend below the lower edge of the load cells. The barrier is fixed to the load cell wall by means of a clamping plate along the upper edge and along the lower edge as shown in Figure 2. The bolts used to attach the clamping plate must not pass through the mounting flange.

[1] A mass, the end of which is between 125 mm and 925 mm high and 1,000 mm deep, is considered to satisfy this requirement.

Figure 2

Mounting details for full width deformable barrier

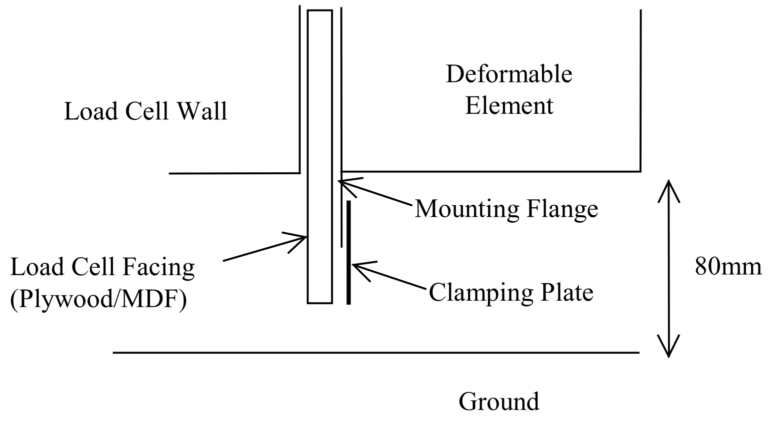
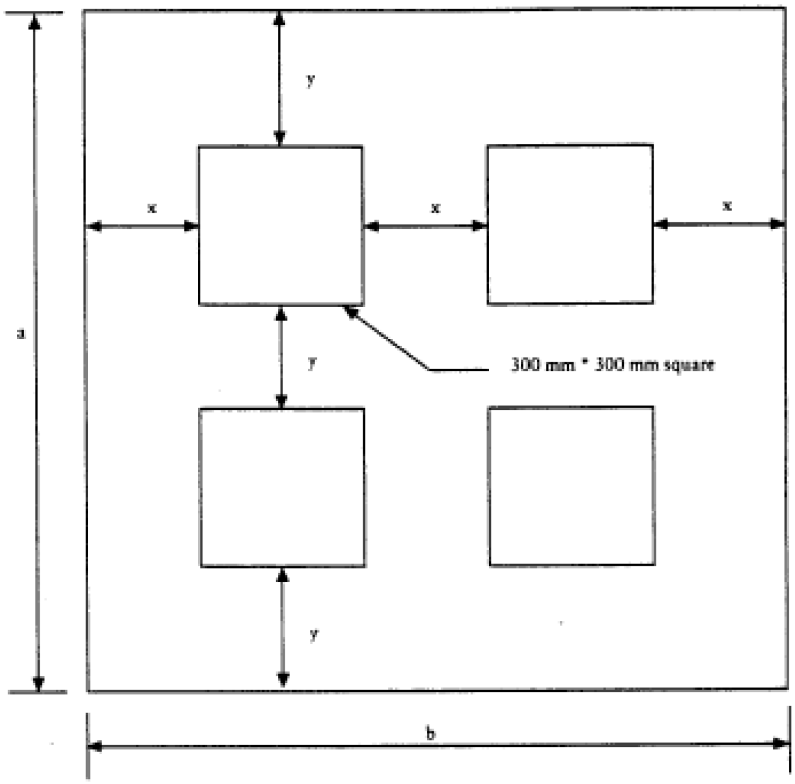
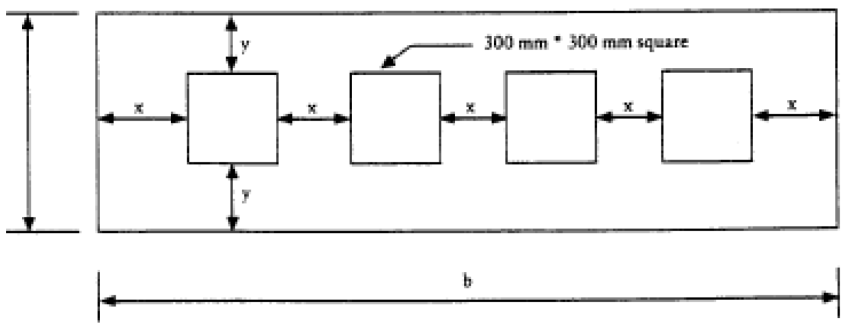


Figure 3

Location of the sample for certification



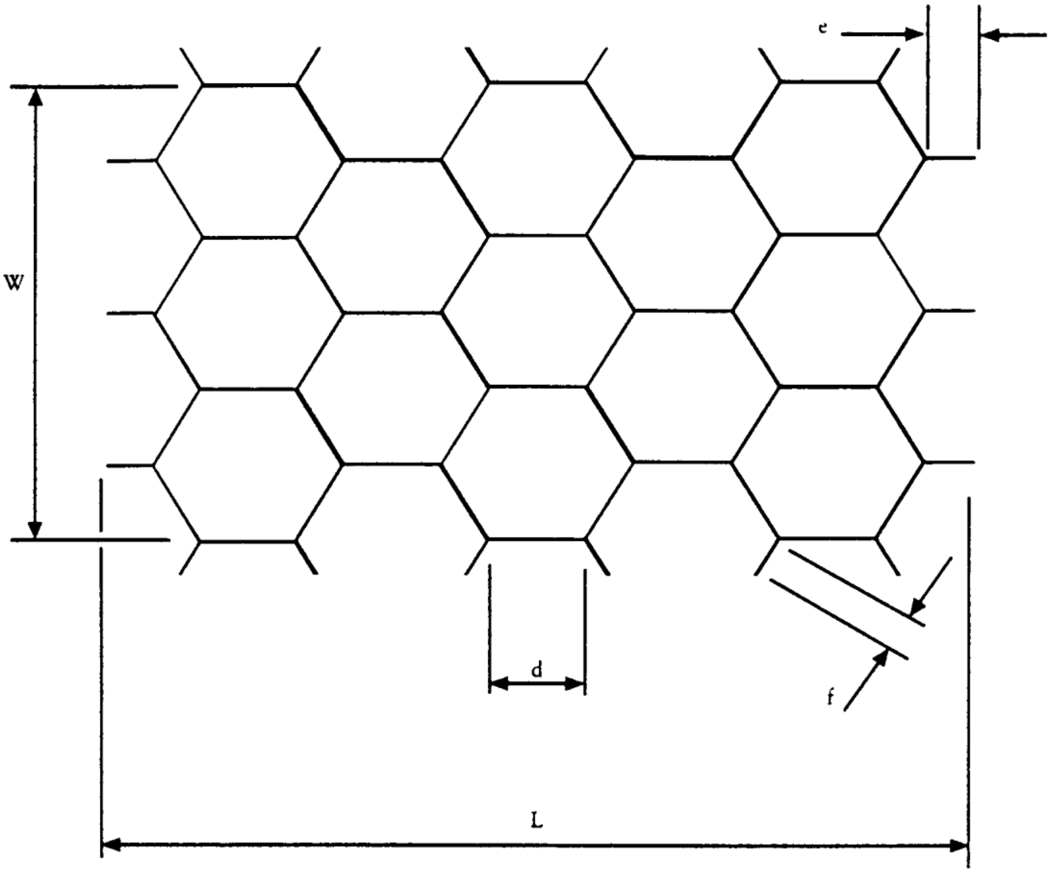
If a ≥ 900 mm: x = 1/3 (b-600mm) and y = 1/3 (a-600mm) (for a ≤ b)



If a < 900 mm: x = 1/5 (b - 1200 mm) and y = ½ (a - 300 mm) (for a ≤ b)

Figure 4

Honeycomb axes and measured dimensions



e = d/2
f = 0,8 mm

Figure 5

Crush force and displacement

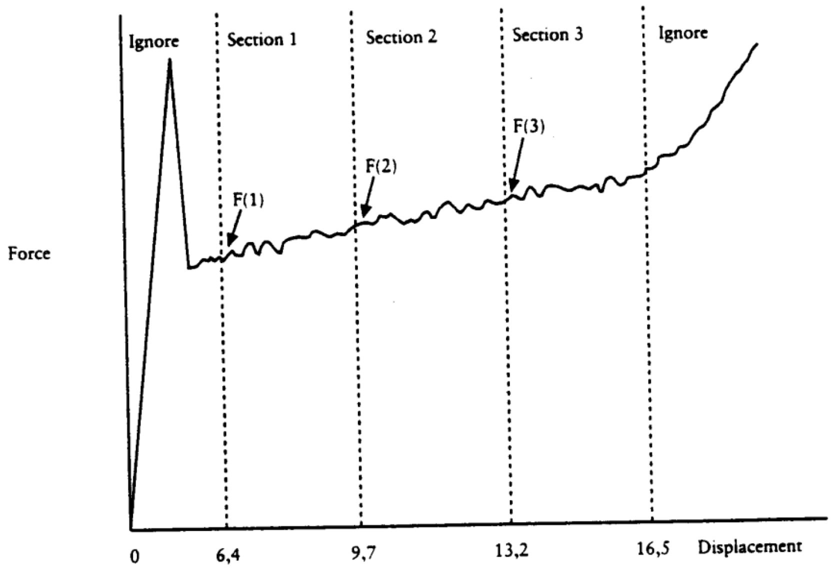
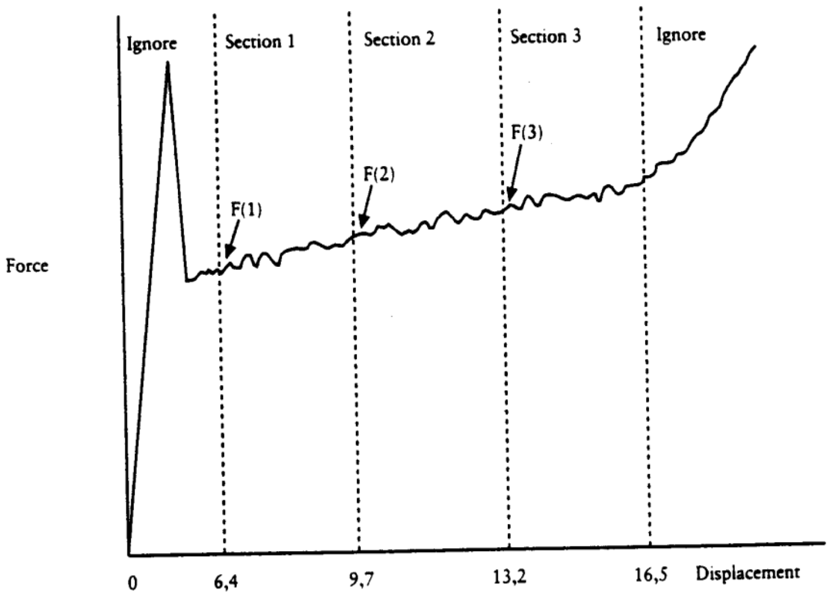


Figure 6

Position of holes for barrier mounting



Hole diameters 9.5 mm.

All dimensions in mm.

Annex 9b DEFINITION OF OFFSET DEFORMABLE BARRIERS

1. COMPONENT AND MATERIAL SPECIFICATIONS

The dimensions of the barriers are illustrated in Figure 1 of this annex. The dimensions of the individual components of the barrier are listed separately below.

1.1. Main honeycomb block

Dimensions:

Height: 650 mm (in direction of honeycomb ribbon axis)

Width: 1,000 mm

Depth: 450 mm (in direction of honeycomb cell axes)

All above dimensions should allow a tolerance of ± 2.5 mm

Material: Aluminium 3003 (ISO 209, Part 1)

Foil Thickness: 0.076 mm ± 15 per cent

Cell Size: 19.1 mm ± 20 per cent

Density: 28.6 kg/m^3 ± 20 per cent

Crush Strength: 0.342 MPa +0 per cent -10 per cent 1/

1.2. Bumper element

Dimensions:

Height: 330 mm (in direction of honeycomb ribbon axis)

Width: 1,000 mm

Depth: 90 mm (in direction of honeycomb cell axes)

All above dimensions should allow a tolerance of ± 2.5 mm

Material: Aluminium 3003 (ISO 209, Part 1)

Foil Thickness: 0.076 mm ± 15 per cent

Cell Size: 6.4 mm ± 20 per cent

Density: 82.6 kg/m^3 ± 20 per cent

Crush Strength: 1.711 MPa +0 per cent -10 per cent [1]

1.3. Backing sheet

Dimensions

Height: 800 mm ± 2.5 mm

Width: 1000 mm ± 2.5 mm

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[1] In accordance with the certification procedure described in paragraph 2. of this annex.

Thickness: 2.0 mm ± 0.1 mm

1.4. Cladding sheet

Dimensions

Length: 1700 mm ± 2.5 mm

Width: 1000 mm ± 2.5 mm

Thickness: 0.81 ± 0.07 mm

Material: Aluminium 5251/5052 (ISO 209, part 1)

1.5. Bumper facing sheet

Dimensions

Height: 330 mm ± 2.5 mm

Width: 1000 mm ± 2.5 mm

Thickness: 0.81 mm ± 0.07 mm

Material: Aluminium 5251/5052 (ISO 209, part 1)

1.6. Adhesive

The adhesive to be used throughout should be a two-part polyurethane (such as Ciba-Geigy XB5090/1 resin with XB5304 hardener, or equivalent).

2. ALUMINIUM HONEYCOMB CERTIFICATION

A complete testing procedure for certification of aluminium honeycomb is given in NHTSA TP-214D. The following is a summary of the procedure that should be applied to materials for the frontal impact barrier, these materials having a crush strength of 0.342 MPa and 1.711 MPa respectively.

2.1. Sample locations

To ensure uniformity of crush strength across the whole of the barrier face, eight samples shall be taken from four locations evenly spaced across the honeycomb block. For a block to pass certification, seven of these eight samples shall meet the crush strength requirements of the following sections.

The location of the samples depends on the size of the honeycomb block. First, four samples, each measuring 300 mm x 300 mm x 50 mm thick shall be cut from the block of barrier face material. Please refer to Figure 2 for an illustration of how to locate these sections within the honeycomb block. Each of these larger samples shall be cut into samples for certification testing (150 mm x 150 mm x 50 mm). Certification shall be based on the testing of two samples from each of these four locations. The other two should be made available to the applicant, upon request.

2.2. Sample size

Samples of the following size shall be used for testing:

Length: 150 mm ± 6 mm

Width: 150 mm ± 6 mm

Thickness: 50 mm ± 2 mm

The walls of incomplete cells around the edge of the sample shall be trimmed as follows:

In the "W" direction, the fringes shall be no greater than 1.8 mm (see Figure 3).

In the "L" direction, half the length of one bonded cell wall (in the ribbon direction) shall be left at either end of the specimen (see Figure 3).

2.3. Area measurement

The length of the sample shall be measured in three locations, 12.7 mm from each end and in the middle, and recorded as L1, L2 and L3 (Figure 3). In the same manner, the width shall be measured and recorded as W1, W2 and W3 (Figure 3). These measurements shall be taken on the centreline of the thickness. The crush area shall then be calculated as:

$$A = \frac{(L1 + L2 + L3)}{3} \text{ x } \frac{(W1 + W2 + W3)}{3}$$

2.4. Crush rate and distance

The sample shall be crushed at a rate of not less than 5.1 mm/min and not more than 7.6 mm/min. The minimum crush distance shall be 16.5 mm.

2.5. Data collection

Force versus deflection data are to be collected in either analog or digital form for each sample tested. If analog data are collected then a means of converting this to digital shall be available. All digital data shall be collected at a rate of not less than 5 Hz (5 points per second).

2.6. Crush strength determination

Ignore all data prior to 6.4 mm of crush and after 16.5 mm of crush. Divide the remaining data into three sections or displacement intervals (n = 1, 2, 3) (see Figure 4) as follows:

(1) 06.4 mm - 09.7 mm inclusive,
(2) 09.7 mm - 13.2 mm exclusive,
(3) 13.2 mm - 16.5 mm inclusive.

Find the average for each section as follows:

$$F(n) = \frac{(F(n)1 + F(n)2 + ... + F(n)m)}{m}; \quad m = 1, 2, 3$$

where m represents the number of data points measured in each of the three intervals. Calculate the crush strength of each section as follows:

$$S(n) = \frac{F(n)}{A};\ n = 1, 2, 3$$

2.7. Sample crush strength specification

For a honeycomb sample to pass this certification, the following conditions shall be met:

0.308 MPa ≤ S(n) ≤ 0.342 MPa for 0.342 MPa material

1.540 MPa ≤ S(n) ≤ 1.711 MPa for 1.711 MPa material

n = 1, 2, 3.

2.8. Block crush strength specification

Eight samples are to be tested from four locations, evenly spaced across the block. For a block to pass certification, seven of the eight samples shall meet the crush strength specification of the previous section.

3. ADHESIVE BONDING PROCEDURE

3.1. Immediately before bonding, aluminium sheet surfaces to be bonded shall be thoroughly cleaned using a suitable solvent, such as 1-1-1 Trichloroethane. This is to be carried out at least twice or as required to eliminate grease or dirt deposits. The cleaned surfaces shall then be abraded using 120 grit abrasive paper. Metallic/Silicon Carbide abrasive paper is not to be used. The surfaces shall be thoroughly abraded and the abrasive paper changed regularly during the process to avoid clogging, which may lead to a polishing effect. Following abrading, the surfaces shall be thoroughly cleaned again, as above. In total, the surfaces shall be solvent cleaned at least four times. All dust and deposits left as a result of the abrading process shall be removed, as these will adversely affect bonding.

3.2. The adhesive should be applied to one surface only, using a ribbed rubber roller. In cases where honeycomb is to be bonded to aluminium sheet, the adhesive should be applied to the aluminium sheet only.

A maximum of 0.5 kg/m^2 shall be applied evenly over the surface, giving a maximum film thickness of 0.5 mm.

4. CONSTRUCTION

4.1. The main honeycomb block shall be bonded to the backing sheet with adhesive such that the cell axes are perpendicular to the sheet. The cladding shall be bonded to the front surface of the honeycomb block. The top and bottom surfaces of the cladding sheet shall not be bonded to the main honeycomb block but should be positioned closely to it. The cladding sheet shall be adhesively bonded to the backing sheet at the mounting flanges.

4.2. The bumper element shall be adhesively bonded to the front of the cladding sheet such that the cell axes are perpendicular to the sheet. The bottom of the bumper element shall be flush with the bottom surface of the cladding sheet. The bumper facing sheet shall be adhesively bonded to the front of the bumper element.

4.3. The bumper element shall then be divided into three equal sections by means of two horizontal slots. These slots shall be cut through the entire depth of the bumper section and extend the whole width of the bumper. The slots shall be cut using a saw; their width shall be the width of the blade used and shall not exceed 4.0 mm.

4.4. Clearance holes for mounting the barrier are to be drilled in the mounting flanges (shown in Figure 5). The holes shall be of 9.5 mm diameter. Five holes shall be drilled in the top flange at a distance of 40 mm from the top edge of the flange and five in the bottom flange, 40 mm from the bottom edge of that flange. The holes shall be at 100 mm, 300 mm, 500 mm, 700 mm, 900 mm from either edge of the barrier. All holes shall be drilled to ± 1 mm of the nominal distances. These hole locations are a recommendation only. Alternative positions may be used which offer at least the mounting strength and security provided by the above mounting specifications.

5. MOUNTING

5.1. The deformable barrier shall be rigidly fixed to the edge of a mass of not less than 7 x 10^4 kg or to some structure attached thereto. The attachment of the barrier face shall be such that the vehicle shall not contact any part of the structure more than 75 mm from the top surface of the barrier (excluding the upper flange) during any stage of the impact[2]. The front face of the surface to which the deformable barrier is attached shall be flat and continuous over the height and width of the face and shall be vertical ± 1° and perpendicular ± 1° to the axis of the run-up track. The attachment surface shall not be displaced by more than 10 mm during the test. If necessary, additional anchorage or arresting devices shall be used to prevent displacement of the concrete block. The edge of the deformable barrier shall be aligned with the edge of the concrete block appropriate for the side of the vehicle to be tested.

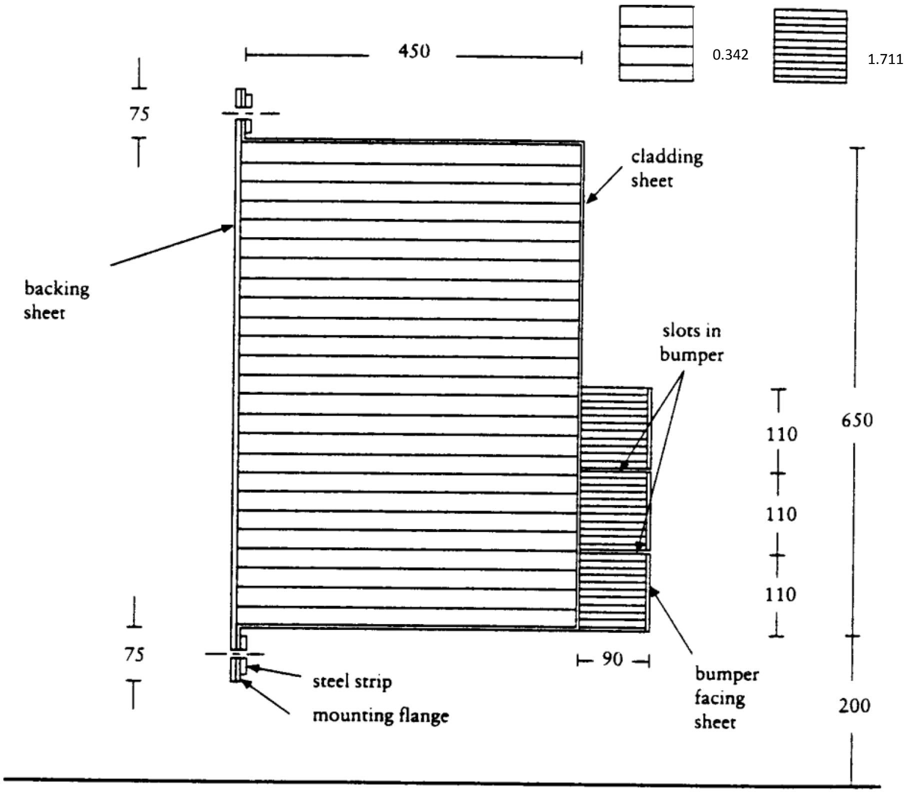
5.2. The deformable barrier shall be fixed to the concrete block by means of ten bolts, five in the top mounting flange and five in the bottom. These bolts shall be of at least 8 mm diameter. Steel clamping strips shall be used for both the top and bottom mounting flanges (see Figures 2 and 6). These strips shall be 60 mm high and 1000 mm wide and have a thickness of at least 3 mm. The edges of the clamping strips should be rounded-off to prevent tearing of the barrier against the strip during impact. The edge of the strip should be located no more than 5 mm above the base of the upper barrier-mounting flange, or 5 mm below the top of the lower barrier-mounting flange. Five clearance holes of 9.5 mm diameter must be drilled in both strips to correspond with those in the mounting flange on the barrier

[2] A mass, the end of which is between 125 mm and 925 mm high and 1,000 mm deep, is considered to satisfy this requirement.

(see paragraph 4.). The mounting strip and barrier flange holes may be widened from 9.5 mm up to a maximum of 25 mm in order to accommodate differences in back-plate arrangements and/or load cell wall hole configurations. None of the fixtures shall fail in the impact test. In the case where the deformable barrier is mounted on a load cell wall (LCW) it should be noted that the above dimensional requirements for mountings are intended as a minimum. Where a LCW is present, the mounting strips may be extended to accommodate higher mounting holes for the bolts. If the strips are required to be extended, then thicker gauge steel should be used accordingly, such that the barrier does not pull away from the wall, bend or tear during the impact. If an alternative method of mounting the barrier is used, it should be at least as secure as that specified in the above paragraphs.

Figure 1

Deformable barrier for offset frontal impact testing



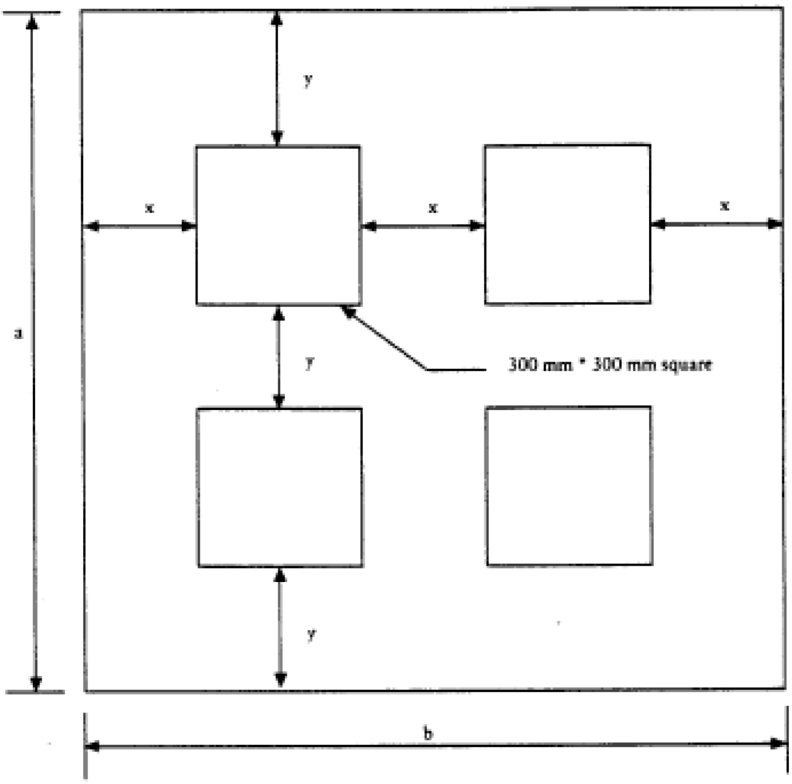
Ground

Barrier width: 1 000 mm

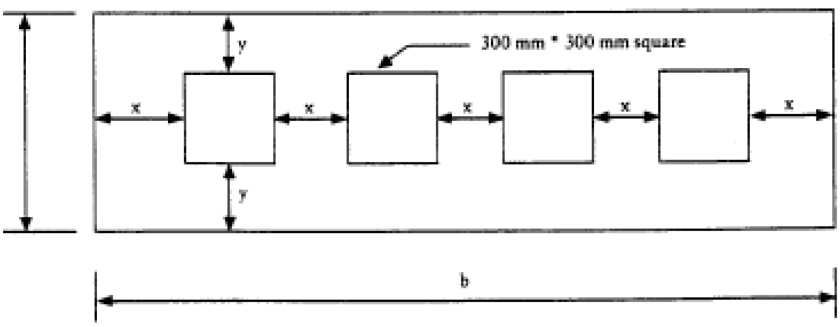
All dimensions in mm.

Figure 2

Location of the samples for certification



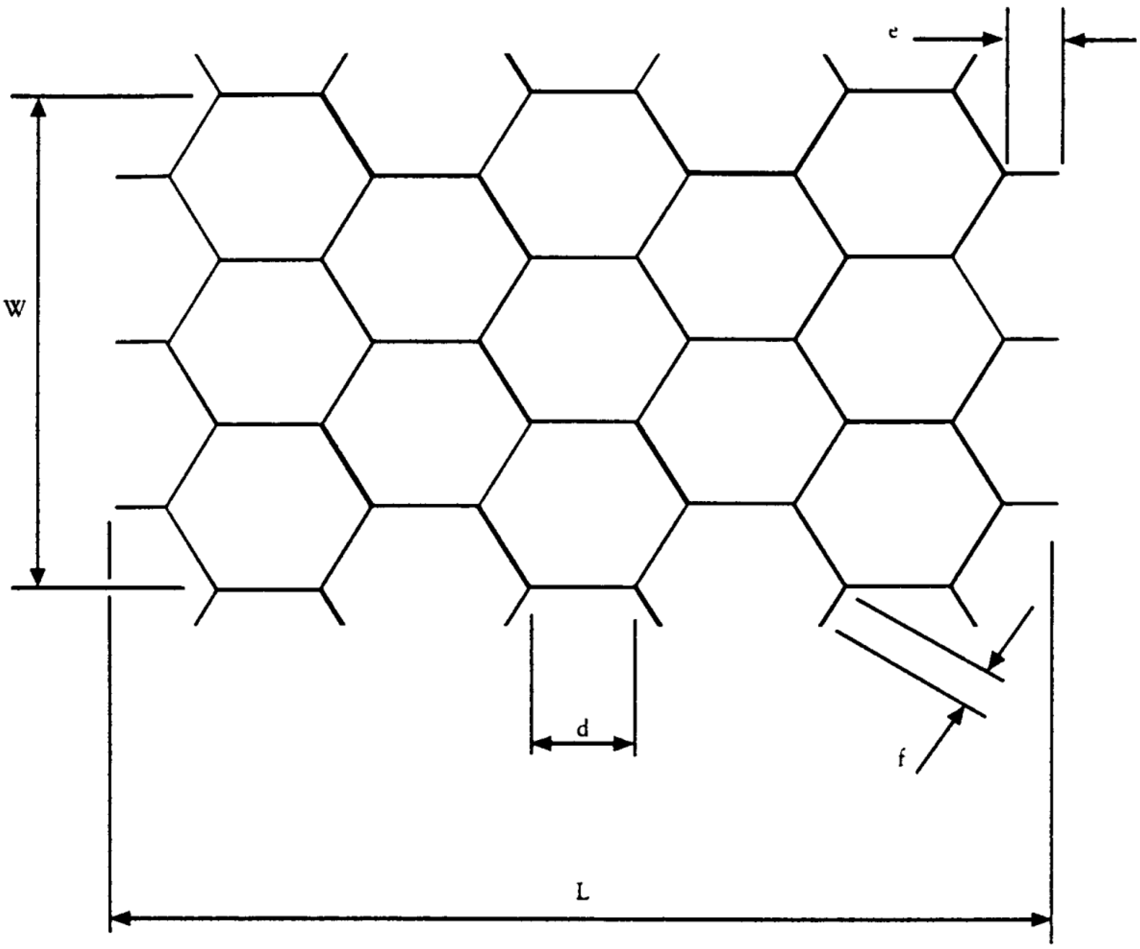
If a ≥ 900 mm: x = 1/3 (b-600mm) and y = 1/3 (a-600mm) (for a ≤ b)



If a < 900 mm: x = 1/5 (b - 1200 mm) and y = ½ (a - 300 mm) (for a ≤ b)

Figure 3

Honeycomb axes and measured dimensions



e = d/2
f = 0,8 mm

Figure 4

Crush force and displacement

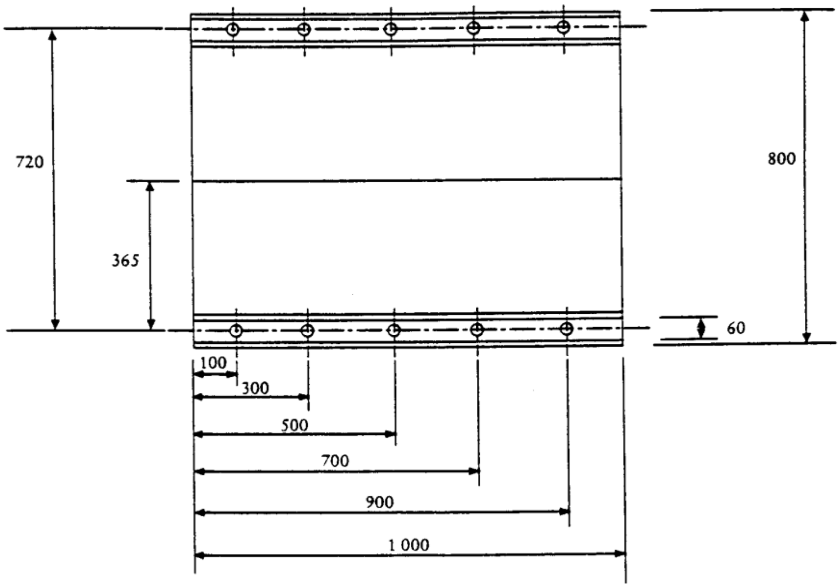
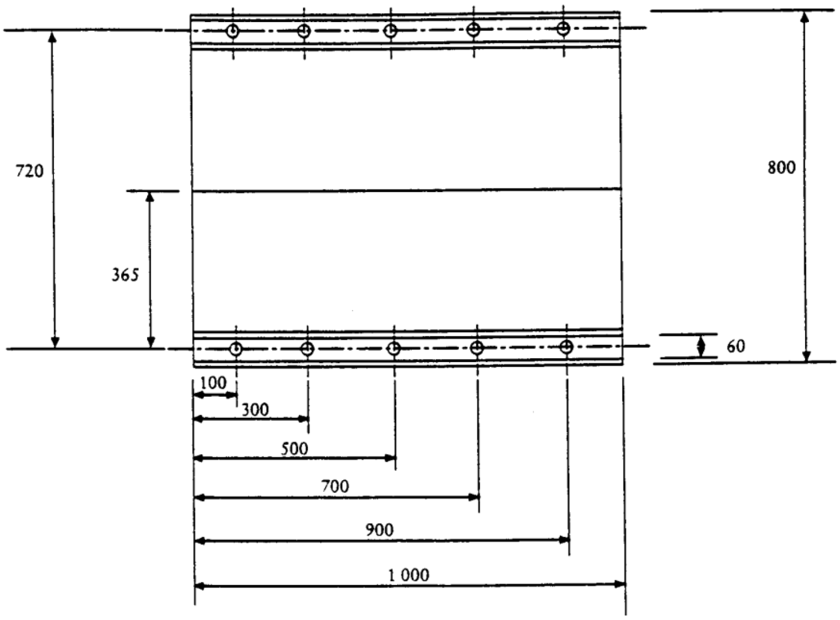


Figure 5

Position of holes for barrier mounting



Hole diameters 9.5 mm.

All dimensions in mm.

Annex 11 LOAD CELL WALL INSTRUMENTATION AND DATA PROCESSING

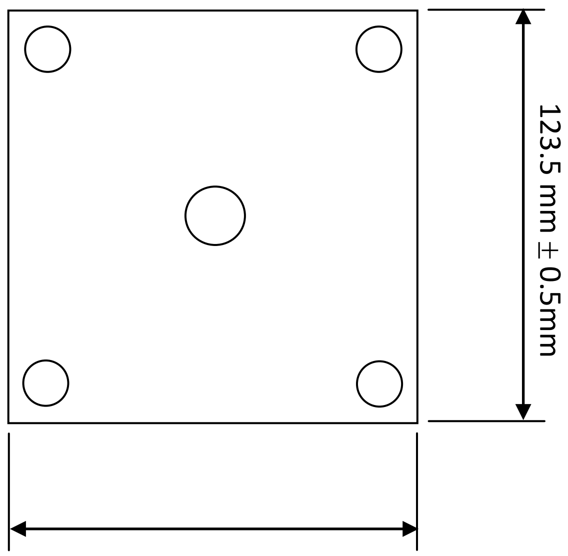
1. The load cell wall is to be formed by a matrix of individual load cells with a spacing of 125mm in the horizontal and vertical directions. The centre spacing of the load cells is 125mm x 125mm. The width of the load cell wall is to be equal to or greater than the width of the deformable barrier and to be exactly divisible by 250mm. The height is to be equal to or greater than the height of the deformable element. [Width 2000mm, height 1000mm]. The lower edge of the load cell wall is to be parallel to the ground and at a height of 80mm relative to the ground. The load cell wall is to be rigidly attached to the barrier with its front face in the same plane as the front face of the barrier.

1.1 *Dimensions and layout*

Each load cell tile on the load cell wall (LCW) has a nominal frontal area of 125mm x 125mm. However, when mounted on the LCW the load cells must have sufficient clearance between the adjacent cells to prevent interaction of the load cell tiles under maximum shear loads. The suggested external dimensions of each individual load cell face in the LCW are shown.

Figure 1

External dimensions of individual load cells



1.2 Each load cell shall be faced with an 18mm thick MDF panel the same size as the load cell face. Any of these MDF facings which become damaged (e.g. dented, split, etc.) should be replaced with undamaged MDF facings.

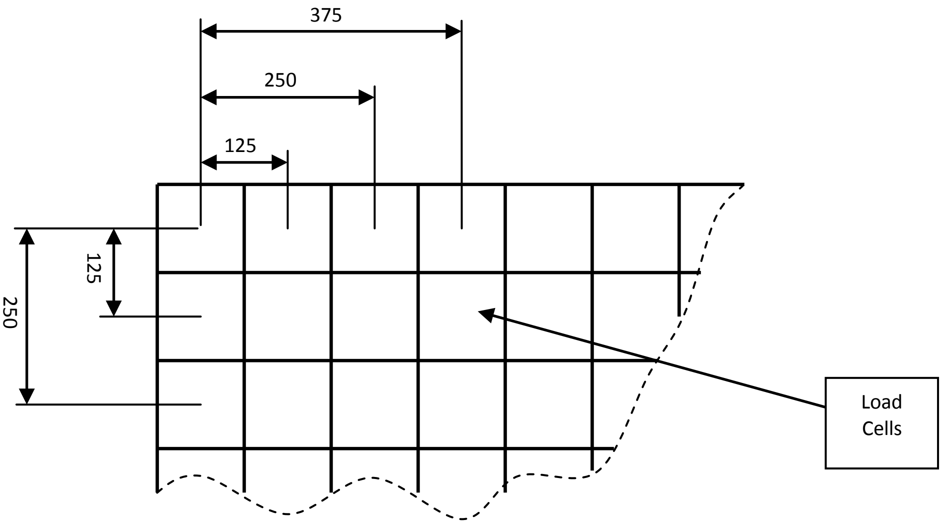
1.3 Each load cell must have threaded holes on the loading face to allow the mounting of deformable barrier faces and the MDF facings. A suggested pattern of holes is shown in the previous figure.

1.4 The full load cell wall, for the purposes of the FWDB test, is to comprise of 128 load cells arranged in a matrix of cells 16 wide by 8 high. The full LCW should have frontal dimensions of 2000mm wide by 1000mm high. The height of the bottom of the LCW above ground should be adjustable. [For the FWDB test, the height of the bottom of the LCW above ground is 80 ±2 mm.]

1.5 The load cells shall be spaced such that the centre of each load cell is 125mm apart in the vertical and horizontal direction. This spacing shall be measured from the centre of the uppermost corner cell on the load cell wall in order to avoid compound errors. This can be achieved by mounting the load cells on a backplate to provide the precise location of each load cell.

Figure 2

Organisation of individual load cells in an array



1.6 The impact face of the load cell wall, including MDF facings, should be flat - no cell should be either recessed or protrude relative to any of its surrounding cells. The surface flatness is check by offering up a flat edge to the load cell wall – this flat edge should bridge two or more load cells. There should be no visible gap [greater than 0.5mm] between the flat edge and the surface of a load cell. If any cells are found to protrude or be recessed, remedial action should be taken to correct this.

1.7 Technical Specifications of individual Load Cells

Nominal area of each load cell impact face	125 x 125mm
Rated load	300kN
Safe overload	600kN
Shear load	100kN
Offset loading error	< 3% (300kN)
Linearity error	< 1.1% (300kN)
Compression / Shear load crosstalk	< 0.5% (300kN)
Cell Mass	< 6kg

Mass difference tolerance between load cells	± 0.2kg
Dynamic response	> 10kHz
Resonant frequency	> 5kHz
Operational temperature range	0^{o}C to $+70^{o}$C

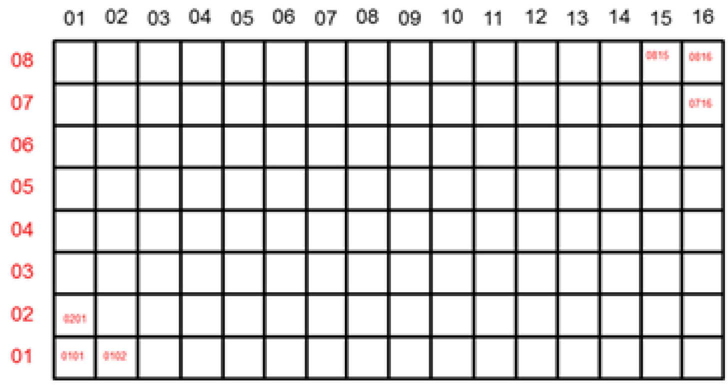
2. Calculation of Compatibility Metric

2.1 All LCW channels are recorded according to SAE J211 and filtered to CFC 60 before further processing

2.2 Each load cell position is labelled by row and column with row 1 and column 1 being in the left lower corner of the LCW when looking in the vehicle's direction of motion. The load in the X direction for each load cell is labelled L_{ij} were *i* is the row and *j* is the column label.

Figure 3

Load Cell Wall numbering



2.3 The row loads F*k* are calculated by summing the load cell measurements in all columns by the following equation at each sampling point:

$$\mathrm{F}k = \sum_{j=1}^{16} L_{k,j} \quad \text{where } k\text{=1,8}$$

2.4 Calculation of Structural Alignment metric

The maximum value of the row loads F2, F3, and F4 are up to 40 ms after barrier contact. The combined loads in row 3&4 (F4+F3) and the maximum total cell wall loads(F_T) for each sample point are calculated from:

$$\mathrm{F4+F3} = \sum_{i=3}^{4} \sum_{j=}^{16} L_{i,j}$$

$$F_T = \sum_{i=1}^{8} \sum_{j=}^{16} L_{i,j}$$

and are used to calculate F_{T40} which is the maximum value of F_T up to 40 ms

2.5 Requirements for Structural Alignment metric

The vehicle fulfils the structural alignment criteria if one of the following conditions is met

– Condition 1

- $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
- $F4 \geq [MIN(100, 0.2F_{T40})$ kN
- $F3 \geq [MIN(100, 0.2F_{T40})$ kN]

Condition 2

- $F4 + F3 \geq [MIN(200, 0.4F_{T40})$ kN
- $F4 \geq [MIN(100, 0.2F_{T40})$ kN
- $F3 \geq [MIN((100\text{-}LR), (0.2F_{T40}\text{-}LR))]$

– where:

  - Limit Reduction (LR) = [MIN([F2-70])] kN, $0 \leq LR \leq$ [50 kN]

Annex 12 INTRUSION MEASUREMENTS

Measurement Methods and Acceptance Values

1 For vehicle deformation and intrusion measurements a 3D measuring system which is capable of recording 3 dimensional co-ordinates of a point in space can be used. A tolerance of +/- 1mm is applicable to such a system. The system requires an axis system to be set up relative to the object to be measured, typically the transverse, longitudinal and vertical directions of a vehicle. An origin is first needed, followed by a point on the positive x axis and then a point in the positive x-y plane. Since the front of the vehicle is highly deformed after the impact, it is simplest to use some structure at the rear of the vehicle as a reference for measurement; this obviates the need to level the car after testing, the accuracy of which is limited. Most of the procedure which follows relates to the setting up of these axes.

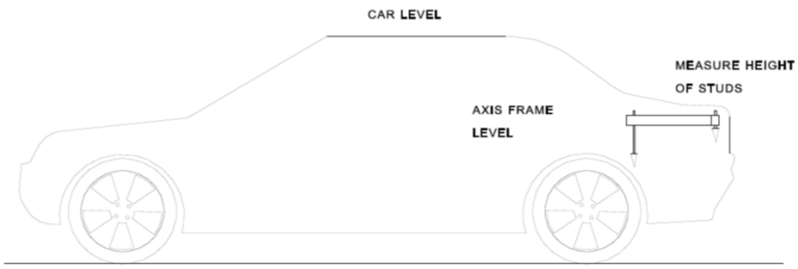
2 Before Test

Remove the carpet, trim and spare wheel from the luggage compartment. The plastic trim or rubber seals that might influence the latching mechanism should be re-fitted once the intrusion measurements have been recorded. This is to ensure that any opening of the rear door during the impact is not caused by the omission of some part of the trim around the latching mechanism.

Locate the vehicle axis reference frame (see Figure 2.1) centrally to the rear of the vehicle.

Figure 1

Preparation of vehicles axis reference frame



2.1.1 Level the reference frame.

2.1.2 Measure and record the stud heights of the reference frame. These will be used after the test to help reset the reference frame, if required.

2.1.3 If it is necessary to lean on the vehicle to reach the following points, the vehicle should be

2.1.4 Set up the vehicle co-ordinate axes in the 3D arm or similar device.

2.1.5 Mark and record the position of at least 5 datum points on the rear of the vehicle. These points should be on structures which are not expected to be deformed in the test and should be positioned such that they have wide spaced locations in three dimensions and can all be reached with the 3D measuring system in one position.

2.1.6 Working on the passenger side of the vehicle determine and mark the positions on the B-post which are:

i) at a distance of 100 mm above the sill.
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

All points should be as close as possible to the rubber sealing strip around the door aperture.

2.1.7 Measure and record the pre-impact positions of the two door aperture points.

2.1.8 Working on the driver's side of the vehicle determine and mark the positions on the A and B posts which are:

i) at a distance of 100 mm above the sill.
ii) at a distance of 100 mm beneath the lowest level of the side window aperture.

All points should be as close as possible to the rubber sealing strip around the door aperture.

2.1.9 Use the arm to measure the pre-impact positions of the marks identified.

2.2 After Test

2.2.1 Remove the dummies according to Annex 5 and remove the data acquisition and emergency abort equipment (if fitted) from the luggage compartment.

2.2.2 Use any 3 of the 5 datum points at the rear of the vehicle, and their pre-impact measurements, to redefine the measurement axes.

2.2.3 If the axes cannot be redefined from any 3 of the datum points relocate the axis reference frame in the same position as in Section 2.1.2. Set the studs of the frame to the same heights as in Section 2.1.5 (Figure 2). The frame should now be in the same position relative to the car as it was before impact. Set up the measurement axes from the frame.

2.2.4 Record the post-impact positions of the B-post points on the unstruck passenger's side of the vehicle.

2.2.5 Compare the vertical co-ordinate of the B-post sill point before (Section 1.1.6) and after (Section 1.1.8) the test.

2.2.6 Find the angle ϴ that best satisfies the following equation: z = - x'sinϴ + z'cosϴ for the B-post sill point (where z = pre impact vertical measurement and x',z' = post-impact longitudinal and vertical).

2.2.7 Transform the post impact longitudinal and vertical measurements (x',z') using the following equations.

$$\begin{bmatrix} X' \\ Z' \end{bmatrix} = \begin{bmatrix} cos\Theta & sin\Theta \\ -sin\Theta & cos\Theta \end{bmatrix} \begin{bmatrix} x' \\ z' \end{bmatrix}$$

2.2.8 Where □ is the angle determined in Section1.2.6. X and Z should now be in the same frame of reference as the pre-impact measurements.

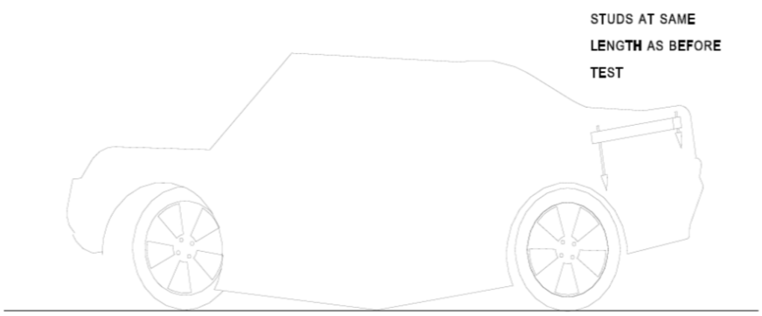
2.2.9 From the pre-impact and adjusted post-impact data collected, determine

i) the rearward movement of the A-post at waist level
ii) the reduction in width of the door aperture at waist and sill levels

2.2.10 Record these intrusion measurements in the test details.

Figure 2

Resetting the vehicle axis reference frame



2.3 The A-Pillar intrusion levels shall not exceed 50 mm.

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SEVENTH FRAMEWORK PROGRAMME

FIMCAR
XII – Influence on Other Impact Types

FIMCAR
frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

The objective of this deliverable is to describe the expected influence of the candidate test procedures developed in FIMCAR for frontal impact on other impact types. The other impact types of primary interest are front-to-side impacts, collisions with road restraint systems (e.g. guardrails), and heavy goods vehicle impacts. These collision types were chosen as they involve structures that can be adapted to improve safety. Collisions with vulnerable road users (VRU) were not explicitly investigated in FIMCAR. It is expected that the vehicle structures of interest in FIMCAR can be designed into a VRU friendly shell.

Information used for this deliverable comes from simulations and car-to-car crash tests conducted in FIMCAR or review of previous research. Three test configurations (full width, offset, and moving deformable barriers) were the input to the FIMCAR selection process. There are three different types of offset tests and two different full width tests. During the project test procedures could be divided into three groups that provide different influences or outcomes on vehicle designs:

1. The ODB barrier provides a method to assess part of the vehicles energy absorption capabilities and compartment test in one test
2. The FWRB and FWDB have similar capabilities to control structural alignment, further assess energy absorption capabilities, and promote the improvements in the occupant restraint system for high deceleration impacts.
3. The PDB and MPDB can be used to promote better load spreading in the vehicle structures, in addition to assessing energy absorption and occupant compartment strength in an offset configuration.

The consortium selected the ODB and FWDB as the two best candidates for short term application in international rulemaking. The review of how all candidates would affect vehicle performance in other impacts (beside front-to-front vehicle or frontal impacts with fixed obstacles) however is reported in this deliverable to support the benefit analysis reported in FIMCAR. The grouping presented above is used to discuss all five test candidates using similarities between certain tests and thereby simplify the discussion.

The common theme is the potential to structurally align vehicle components with the opposing structures. In some cases, like truck RUPs (Rear Underrun Protection), requirements of the collision partner are not ideal for passenger vehicle designs. Introduction of performance requirements that harmonise geometric alignment will support future harmonisation of crashworthiness designs, independent of passenger cars. International harmonisation of concepts like the common interaction zone will improve future vehicle and infrastructure safety performance.

The final assessment approach that was developed within the FIMCAR project duration does not have a horizontal load spreading assessment. The FWDB was not suitable for this procedure and a validated (M)PDB deformation metric for load spreading in the vertical and horizontal directions is still in the final stages of development. Preferably, a load spreading metric could be introduced into a future offset test like the (M)PDB. The load spreading metric would address many impact conditions identified in impacts with vehicle sides, HGVs, and roadside equipment.

Stiffness issues with current vehicle designs are not expected to be affected negatively by the FIMCAR approach. The combination of a FWDB and ODB will create a balanced frontal

stiffness that cannot be expected to be softer than vehicle side structures, nor stiffer than HGV frames. Current compartment strength needs to be maintained and the frontal stiffness can be tuned to appropriate levels through the combined full width and offset test requirements.

The current test candidates and final assessment procedure selected by FIMCAR do not have any obvious negative implications for side impacts, HGV impacts, nor impacts with road equipment. The worst case scenario is that the introduction of a FW metric with minimum load requirements in Rows 3&4 can lead to sub-optimisation and worsened horizontal load spreading. This risk is small and the selection of a FWDB will likely mitigate this side effect. The deformable barrier dampens the peak loads and introduces a need to have larger contact surfaces to generate sufficient loads in the assessment area.

The current assessment approach in FIMCAR may introduce limited improvements for the investigated collisions, but it is expected that the harmonisation of interaction areas of HGV and road side equipment will allow to a convergence to compatible structural designs in the road and traffic network.

1 INTRODUCTION

1.1 FIMCAR Project

For the real life assessment of vehicle safety in frontal collisions the compatibility (described by the self and partner-protection level) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition, another procedure (tests with a moving deformable barrier) is under discussion in today's research programmes.

Within the FIMCAR project, different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to describe the expected influence of the candidate test procedures developed in FIMCAR for frontal impact on other impact types. The other impact types of primary interest are front-to-side impacts, collisions with road restraint systems (e.g. guardrails), collisions with objects and heavy goods vehicle impacts. Collisions with vulnerable road users were not explicitly investigated in FIMCAR. It is expected that the vehicle structures of interest in FIMCAR are designed into a VRU friendly shell.

Information used for this deliverable comes from simulations and car-to-car crash tests conducted in FIMCAR or review of previous research.

1.3 Structure of this Deliverable

This deliverable starts with a brief review of the test candidates discussed within in FIMCAR and the rational for selecting the FIMCAR assessment approach. This chapter is followed by a discussion of the expected design changes of vehicles for the different assessment procedures. Based on these findings the implications for the struck car in side impact collisions, the implications for HGV (Heavy Goods Vehicles) impacts, especially rear and front underrun protection devices, and the implications for impacts against safety equipment of infrastructure are analysed. Finally all findings are discussed as a whole.

2 REVIEW OF PRIMARY TEST CANDIDATES

2.1 Introduction

Three test configurations (full width, offset, and moving deformable barriers) were the input to the FIMCAR selection process. There were 2 different offset tests, 2 different full width tests, and 1 MPDB. During the project test procedures could be divided into 3 groups that provide different influences or outcomes on vehicle designs:

1. The ODB barrier provides a method to assess part of the vehicles energy absorption capabilities and compartment test in one test
2. The FWRB and FWDB have similar capabilities to control structural alignment, further assess energy absorption capabilities, and promote the improvements in the occupant restraint system for high deceleration impacts.
3. The PDB and MPDB can be used to promote better load spreading in the vehicle structures, in addition to assessing energy absorption and occupant compartment strength in an offset configuration.

The final decision process and resulting test procedures of the FIMCAR project are presented in FIMCAR Deliverable D6.3 [Thomson 2013]. The consortium selected the ODB and FWDB as the two best candidates for short term application in international rulemaking. The review of how all candidates would affect vehicle performance in other impacts (beside front-to-front vehicle or frontal impacts with fixed obstacles) however is reported in this deliverable to support the benefit analysis reported in FIMCAR Deliverable D1.2 [Edwards 2013]. The grouping presented above is used to discuss all five test candidates using similarities between certain tests and thereby simplify the discussion. An overview of the three test groups is presented in the following sections.

2.2 Off-set Deformable Barrier Procedure (ODB)

The ODB frontal crash test was developed from 1989-1995 [Thomson 2013], and it simulates the collision of the tested vehicle against another vehicle of similar mass. The main characteristic is the use of a deformable barrier, which was developed by the European Enhanced Vehicle Safety Committee (EEVC). The test consists of a frontal crash where the car impacts the barrier which overlaps of 40% of the driver's side of the vehicle (Figure 2.1). This is the current procedure described in UN-ECE Regulation 94 and European Directive 96/79/EC where the test speed is 56 km/h. From 1996, Euro NCAP [Euro NCAP 2013] adopted this procedure for a European consumer information program with the speed increased up to 64 km/h.

FIMCAR has chosen the ODB test as the main candidate for evaluating the self-protection of the vehicle and ensuring the compartment strength is maintained at current levels. A drawback of the method is that it does not allow for direct measurements of the vehicle structure for compatibility assessment.

Details of the ODB test method with proposed modifications are available in FIMCAR Deliverable D2.2 [Lazaro 2013/1]

Figure 2.2: ODB Test Configuration

2.3 Full Width Rigid/Deformable Barrier Procedure (FWR/DB)

The FWDB is a modification of the standard Full Width Rigid Barrier that has been used for frontal impact protection for several decades. The FWDB and FWRB use the same approach for assessing structural alignment of vehicles using a Load Cell Wall consisting of an array (cell size 125x125) of load cells and both tests promote self-protection for vehicles' occupants in high overlap tests. Although very similar, the FWDB offered some technical advantages over the FWRB and was the final selection. The decision process for FIMCAR is described in FIMCAR Deliverable D6.3 [Thomson 2013]. The FWDB barrier has a 300 mm honeycomb barrier. The honeycomb has two layers, a soft initial layer and a stiff rear layer. The honeycomb helps to damp out the engine contact forces on the wall. The impact speed for the test is proposed to be 50 km/h.

The vehicle structures are assessed with forces summed across the Load Cell Wall rows with the goal to promote structural alignment of primary energy absorbing structures (PEAS) in an vertical area between 406-508 mm (above ground), referred to as a common interaction zone and known as the Part 581 zone in US federal regulations [GPO 2011]. The proposed metric for the FWDB, presented below, requires a minimum force in Rows 3&4 of the Load Cell Wall in the first 40 ms of impact. A similar approach was proposed for the FWRB but with a shorter assessment period and no possibility for assessing loads under Row 3 without a second test.

- Up to time of 40 msec:
  - F4 + F3 ≥ [MIN(200, 0.4F_{T40}) kN
  - F4 ≥ [MIN(100, 0.2F_{T40}) kN
  - F3 ≥ [MIN((100-LR), (0.2F_{T40}-LR))] where:
    - F_{T40} = Maximum of total LCW force up to time of 40 msec
    - Limit Reduction (LR) = [F2-70] kN and 0 kN ≤ LR ≤ 50* kN

*Note values for Limit Reduction to be confirmed taking into account differences in test speed

Because of the similarities in the test evaluation, analyses of a full width test group (FWRB and FWDB) are presented in the following chapters. More details of the FW tests (Figure 2.3) and their development are available in FIMCAR Deliverable 3.2 [Adolph 2013].

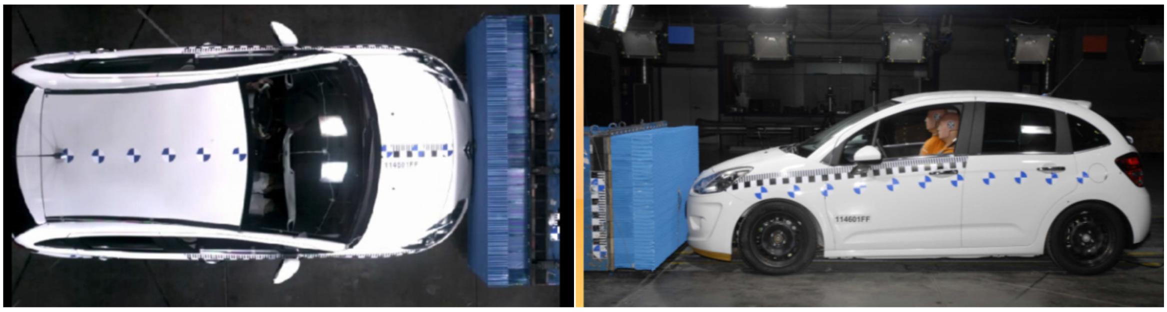

Figure 2.3: FWDB Test Configuration

2.4 Progressive Deformable Barrier / Moving Progressive Deformable Barrier (M)PDB

An alternative to the ODB fixed barrier testing is the (M)PDB approach that was part of the FIMCAR research activities in Work Packages 2 and 4. Both tests incorporate the deformable barrier face developed in France and are evaluated in FIMCAR Deliverables D2.1, D2.2 and D4.2 [Lazaro 2013/1, Lazaro 2013/1, Versmissen 2013]. The test parameters are presented in *Table 1*. As shown in Figure 2.4*:* the honeycomb barrier can be mounted on a fixed or moving barrier of fixed weight.

Table 1: Test Characteristics for (M)PDB.

PDB		MPDB	
Deformable barrier:	PDB v8	Trolley mass:	1500kg
Vehicle speed:	50 km/h	Deformable barrier:	PDB v8
Overlap:	50%	Trolley speed:	50 km/h
Angle:	0 degrees	Vehicle speed:	50 km/h
		Overlap:	50%
		Angle:	0 degrees

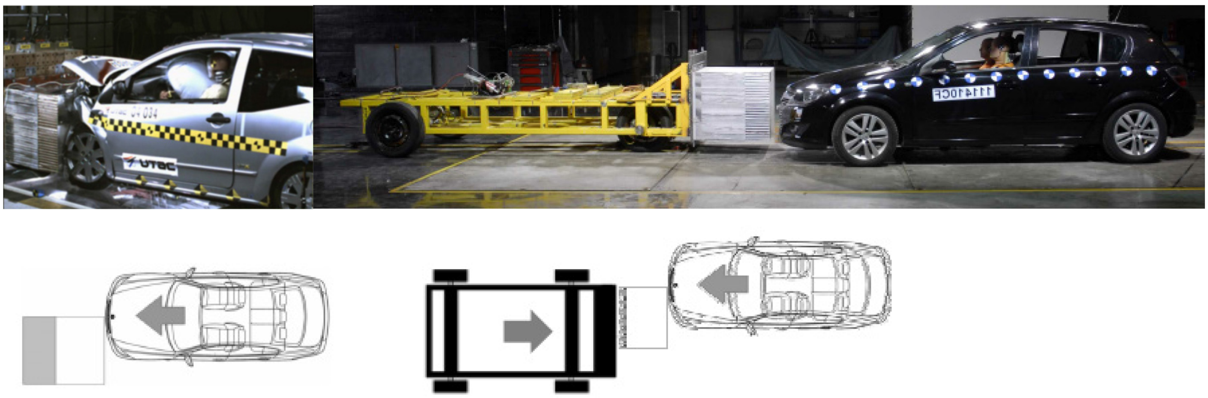

Figure 2.4: Test Configuration PDB (left) MPDB (right).

The PDB barrier honeycomb crush strength is progressively stiffer and is intended to represent an average car. The deformation pattern of the barrier after the test is scanned and used to evaluate the vehicle's compatibility performance for both the PDB and (M)PDB tests. The assessment process for both tests is thus identical. The main difference between the PDB and MPDB test is the delta-v dependency introduced by the moving trolley. Vehicles lighter than the trolley are subjected to a higher test severity than the equivalent PDB test speed and vice-versa.

Assessment of the (M)PDB barrier deformations are under development and are recommended for further development after FIMCAR. The 3D scan information after a test is used to discriminate between vehicles with homogeneous deformations Figure 2.5 (left) or local stiffnesses, Figure 2.5 (right).

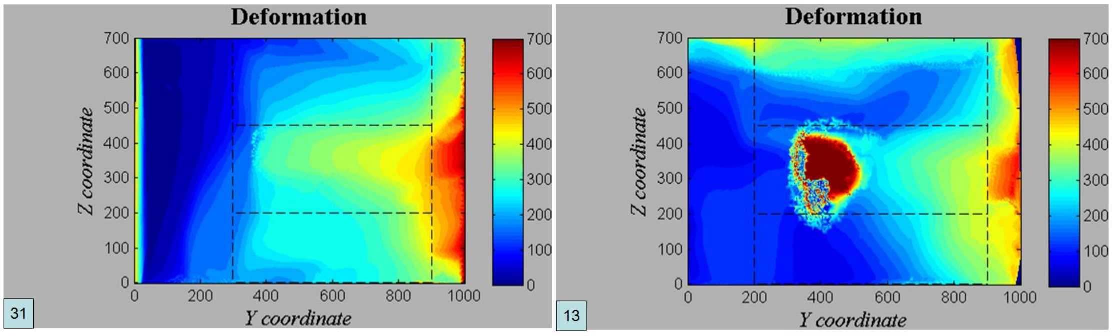

Figure 2.5: PDB Scan Examples.

3 EXPECTED DESIGN CHANGES FOR VEHICLES

The combination of the full width and off-set test procedure has two main advantages:

1) it creates two different structural loading conditions that are representative of the majority of real world frontal crashes
2) it produces an assessment environment with different restraint system loads and sensing requirements to avoid single point optimisation

The introduction of any new frontal impact test procedures must produce modifications to the vehicle fleet to improve crashworthiness performance and thereby improve occupant safety. A positive benefit to society is needed and FIMCAR Deliverable D1.2 [Edwards 2013] describes the expected outcomes for three options:

- No change (only the existing ODB)
- Addition of a FW test to the existing ODB
- Adding the FW test and replacing the ODB with a (M)PDB

These options mirror the grouping of test candidates used in this deliverable.

FIMCAR has developed a list of vehicle characteristics which are desirable for good crashworthiness performance in frontal impacts (seen in Figure 3.1) and also identifies which test methods are most suitable to assess and control them. The remainder of this chapter will discuss the vehicle design changes expected from implementation of the different test methods. This information will then be used in the subsequent chapters to describe the likely consequences of the new frontal impact requirements investigated by FIMCAR on other impact types.

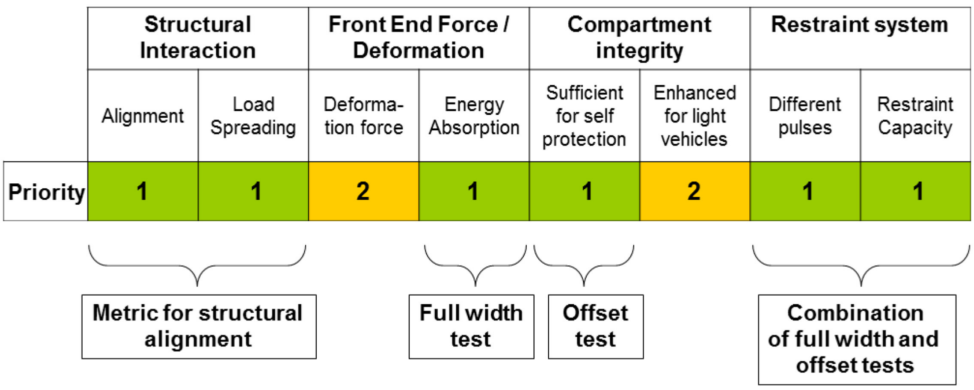

Figure 3.1: FIMCAR Compatibility Characteristics and Priorities.

3.1 Off-set Deformable Barrier Procedure (ODB)

The ODB test procedure selected by FIMCAR will probably result in no significant design changes in vehicles over those that have already been observed because it has already been in place for many years. The main contribution of the ODB is the promotion of a strong and stable occupant compartment in an offset impact condition. The concentrated loading on one side of the vehicle promotes a strong foot well and A-pillar/sill combination to resist intrusion. The test also requires the vehicle structure to absorb its own kinetic energy (minus that absorbed in the barrier) in the offset configuration. The addition of a requirement for A-pillar deformations to be less than 50 mm will guarantee sufficiently strong occupant compartments by enforcing the stability of the forward occupant cell. There is no explicit requirement for compartment stability in the current UN-ECE Regulation 94 that ensures a minimum level for Europe. Euro NCAP tests tend to promote stronger compartment designs than R94 but this is not a mandatory test.

The ODB test procedure encourages vehicles to have a stiff compartment which is useful in in car-to-car accidents and car-to-objects accidents. However, impacts against narrow objects at the corner or in the middle of the vehicle will not be addressed with the ODB test procedure. The ODB test procedure is the state-of-the-art for self-protection in single vehicle accidents and statistics show it is the same level for light and heavy vehicles [Chauvel 2009, Pastor 2009/1, Pastor 2009/2]. In contrast, heavy vehicles can be more aggressive in car-to-car collisions when they collide with lighter vehicles. A mass difference in car-to-car collisions creates a higher delta-v in the lighter collision partner. Older vehicle generations have also exhibited issues related to the overcrushing of lighter vehicles and resulting problems with compartment integrity due to a vehicle fleet where frontal forces are proportional to the vehicle mass [Faerber 2007]. The latter problem was not identified in the latest accident analysis in FIMCAR Deliverable D1.1 [Thompson 2013/1]

3.2 Full Width Rigid/Deformable Barrier Procedure (FW)

The FW test procedures fulfil two objectives in the FIMCAR project. They create a requirement for structural alignment that has shown to be beneficial in car-to-car collisions. The structures located 406-508 mm above the ground will be required to exceed a threshold force in the first stages of the collision and thus reduce the risk for over/underride. Some basic requirements for vertical load spreading are included because the structures need to provide a certain level of force distribution in Rows 3 and 4 with possible extension to Row 2.

The FW test procedures both create a stiff pulse that will require occupant restraint systems to be improved compared to vehicles designed only for the ODB. This high pulse test also promotes a change in the frontal force level designs so that the ride down accelerations will be suitable for the injury criteria selected. Without the FW, smaller vehicles can exploit the current ODB and have stiffer front structures than desirable, causing short ride down distances and high acceleration loads on the occupant.

3.3 (Moving) Progressive Deformable Barrier Procedure (M)PDB

Although not part of the final selection of test procedures in FIMCAR, the (M)PDB capabilities are presented for information and potential development.

The (M)PDB provides an opportunity to modify the test severity of a vehicle depending on its mass. The PDB test results to date have indicated that the test is more severe for lighter vehicles than heavy vehicles in most cases. In a MPDB test, vehicles lighter than the trolley would experience a more severe crash than if the barrier was fixed. Conversely, vehicles heavier than the trolley would experience a less severe crash severity than if the barrier was fixed. Both of these characteristics are desirable for lighter vehicles, but the consortium ranked this issue as Priority 2 (see Figure 3.1) and severity reference levels for the different vehicle masses have not been resolved. The selection of different test speeds and trolley reference masses was investigated in FIMCAR and the information presented in Table 1 reflects the current status for the procedures.

In addition to the potential to offer the test severity for a vehicle depending on its mass, the (M)PDB offers barrier deformation metrics from the test to promote better load spreading in vehicle designs. The test data from FIMCAR shows that the PDB deformations can be used to identify horizontal load spreading issues in a vehicle and future development could be used to establish thresholds for vehicle performance. Vertical load spreading could also use a similar approach. The advantages of vertical and horizontal load spreading have also been identified in previous research [Faerber 2007, Thompson 2013/1]. Vertical load spreading promotes more robust structures to resist over/underrun behaviour and horizontal load spreading promotes designs that resist fork effect and small overlap issues.

4 IMPLICATIONS FOR SIDE IMPACT

4.1 Review of Current Status of Side Impact

Side impact issues have been recently reviewed by EEVC WG 13 [EEVC 2010]. They conducted a review of injury issues observed in accident analysis, characteristics of different test methods, and cost benefit analyses of different solutions.

Current side impact protection in Europe is controlled by a moving deformable barrier (MDB) test in regulation (UNECE R95 and 96/27/EC) and both MDB and pole impact tests in consumer rating programmes (Euro NCAP). The MDB test device is supposed to represent the force/deflection characteristics of a vehicle front. However, when the properties of the barrier were reviewed by the EEVC group, they were not found to be representative of current vehicles and hence a new advanced energy absorbing barrier was developed recently to address this issue. Critics of the MDB question the relatively even distribution of forces on the side of the struck vehicle which may not be true in a real car-side impact. The pole impact test addresses single vehicle collisions when vehicles depart the roadway and slide sideways into vertical structures. Both tests promote adequate padding and airbag protection systems for occupants and ensuring sufficient structures in the door, sill, and roof to resist intruding objects.

Two recent studies that have investigated side impact compatibility in recent years were found in the literature. These are a study performed by Honda [Takizawa 2009] and one by the EC funded FP6 project APROSYS [Thompson 2007]. Both studies used the following approach:

- To investigate the effect of modifying the characteristics of a Mobile Deformable Barrier (MDB) such as geometry, stiffness, mass, velocity, on the protection offered by a side impacted car.
- To investigate the effect of modifying the characteristics of the frontal structures of an impacting car on the protection offered by a side impacted car.

The APROSYS study was based on FE modelling only whereas the Honda study was based on FE modelling and full-scale testing. The findings from both studies were similar. They are summarised below:

- MDB impacts
    - The main conclusions from the barrier-to-car tests / simulations were that reduction of loading of the target vehicle in alignment with the occupant's upper body in combination with increased structural interaction with the target vehicle's sill were the most important factors relating to an improvement in side impact compatibility. This indicated that matching of the bullet vehicle's vertical stiffness distribution to the target vehicle's stiffness is important, as lower loads are required at the less stiff upper levels of the target vehicle and more load is required at the stiffer sill level.
- Car-to-car impacts
    - The main conclusion from the car-to-car impacts was that structural interaction between bullet and target vehicle structures is important in reducing the risk of injury, whilst stiffness matching between these structures is important to prevent overloading of the target vehicle's structures, in particular the B-pillar by the bumper crossbeam and the sill by the subframe load path.

From these conclusions some guidelines can be derived for changes to a car's front-end structures related to its compatibility in side impact:

- High frontal structures should be discouraged to reduce loading of the impacted car's side in alignment with the dummy.
- Homogeneous structures which interact with more of the impacted car's side structures should be encouraged provided they are not so stiff that the impacting overload the side structures (sill and B-pillar).

4.2 Changes Expected from FWDB

The FWDB currently is designed to promote a front structure that is not too stiff in a car-to-barrier impact. The deformations of a car front during a car-to-car side impact are typically much less than a frontal car-to-barrier impact indicating. The relative stiffness of front structures to side structures was observed in the study by Takizawa et. al. [Takizawa 2007]. Their study showed that reducing the longitudinal stiffness from the standard vehicle reduced the side impact intrusion. However their study did not confirm that the new longitudinal design was still suitable for frontal impact safety. The main influence the FWDB will have on side impacts is the influence of force distributions within the vehicle front end. The common interaction zone addressed by the current metric in Rows 3&4 is quite high relative to the sill in a passenger car. However, the current proposed side barrier AEMDB produces forces particularly between 350 mm and 550 mm (see Figure 4.1) which is aligned with the FW metric in Rows 3&4.

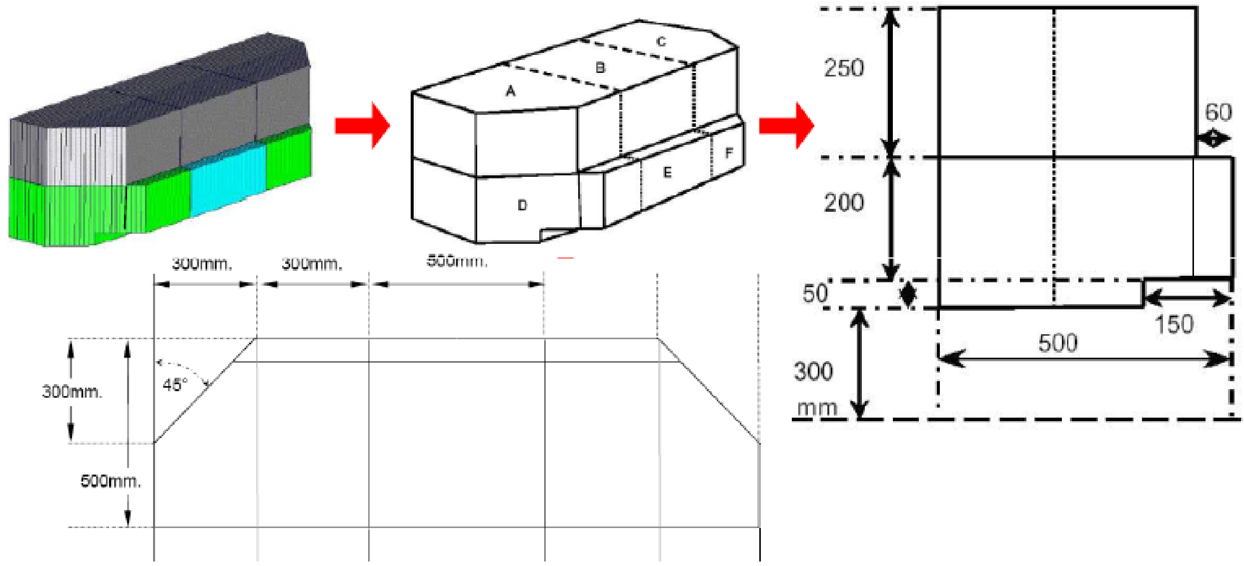

Figure 4.1: Geometry of the AEMDB [EEVC 2010]

Simulation studies [O'Brien 2010] identified the main benefits of different load spreading strategies and summarised in *Table 2* .The main benefits coming from a vehicle designed with the FWDB would be to include some vertical load spreading so that loads are distributed from Row 2 to Row 4. Side impact crash tests were conducted in FIMCAR that highlighted the benefits of having lower load path forward of the front tires [Sandqvist 2013] near the front of the vehicle. Tests and simulations were conducted with a vehicle modified by removing the lower structures identified in Figure 4.2. The sill of the struck vehicle was not contacted directly in any of the tests or simulations, but improved vertical load spreading distributed the deformation over the vehicle side and reduced maximum door intrusion.

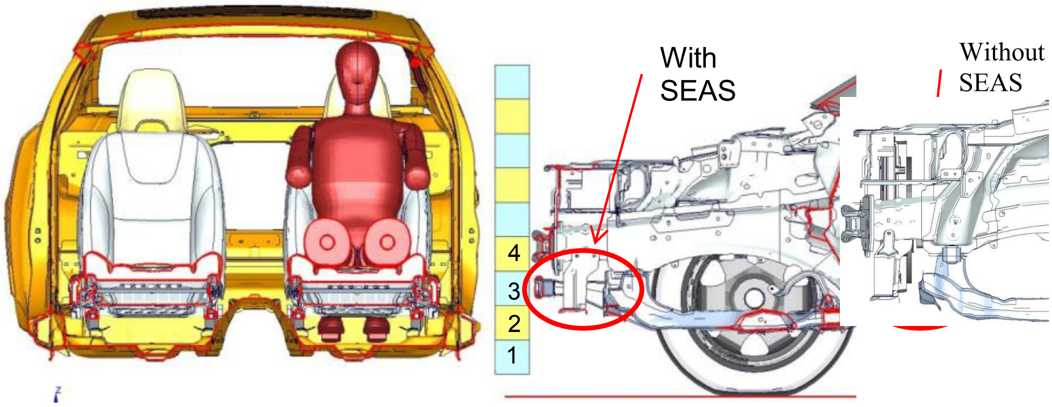

Figure 4.2: Pre-crash alignment compared to load cell wall.

Table 2: Summary of vehicle loading strategies in side impacts [O'Brien 2010].

Horizontally homogeneous front-end	→ Effective when loads are transferred to the struck vehicle's A- and C-pillars. → May be detrimental when loads are focussed on a weak B-pillar.
Vertically homogeneous front-end	→ Effective when loads are transferred to the struck vehicle's sill and floor.
Stiffened door crossbeams	→ Reduce deformation but are not complimentary with front-end homogeneity.
Stiffened B-pillar	→ Complimentary with a horizontally homogeneous front-end structure.
Stiffened sill	→ Complimentary with a vertically homogeneous front-end structure.
Most effective changes to basis models	→ Similar changes are effective for front-to-front and front-to-side collisions. → Stiffening of B-pillar and sill results in complimentary improvements.

The current FWDB metric includes a credit for loads in Row 2 under certain conditions but the FWRB requires an additional test (currently not available) to reliably assess the structures shown in Figure 4.2. The type of test that has been proposed to complement the FWRB is the Over Ride Barrier (ORB) being evaluated in the US [Patel 2009]. FIMCAR numerical simulation analysis shows that meeting the current ORB criteria does not necessarily require well performing cars [Adolph 2013, Stein 2013].

The results from FIMCAR agree with the study by Takizawa et al. [Takizawa 2007]. The combination of FE simulations with different structural concepts, as well as physical tests showed that the best occupant response was encountered when good vertical and horizontal load spreading was achieved. When only one load path (longitudinals) was implemented in the striking vehicle, it was better to keep the structures as low as possible.

Horizontal load spreading is identified in FIMCAR as a desirable vehicle characteristic (Figure 3.1) and load spreading was shown to improve partner protection, particularly when more than one vertical side structure is contacted. The use of a single load path at bumper level can produce aggressive behaviour in front-to-side impacts if weak horizontal load spreading is not complemented with vertical load spreading and load application into the floor of the struck car. The crash tests showed how the cross beam can wrap around the B-pillar and introduce local intrusions in the vehicle side due to the stiffness of longitudinals. Other studies [O'Brien 2010] have confirmed this aggressive behaviour if the horizontal loads are not suitably distributed across the vehicle and a typical example is shown in Figure 4.3.

The results of FIMCAR and external research support the development of a structural alignment metric that controls the height of the structures as well as encouraging vertical load spreading. The Limit Reduction will credit loads in Row 2 that promotes load spreading towards the sill of the struck car during a lateral impact.

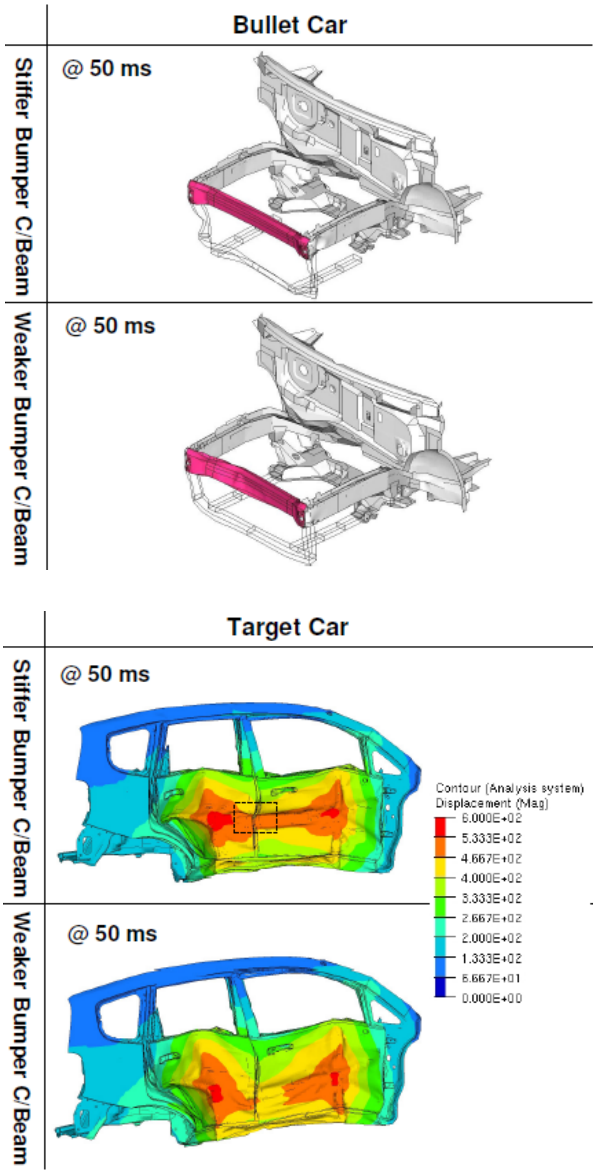

Figure 4.3: Influence of horizontal load spreading on side impact intrusion [Takizawa 2007].

The FW test metrics have no horizontal load spreading components. Vehicle frontal structures will thus not likely exhibit improvements in their horizontal load spreading and improve their compatibility in side impacts. The use of a FWDB will reduce the risk of mis-use of the FW test by exploiting local loadpaths since the force applied to one load cell is, in practice, limited by the crush strength of the honeycomb. The damping characteristics of the FWDB is advantageous over the FWRB in this case.

4.3 Changes Expected from ODB

As mentioned earlier, the existing ODB will not modify future vehicle designs to promote load spreading vertically or horizontally. No additional improvement for side impact protection is expected from the ODB. However, no disadvantages are expected.

4.4 Changes due to (M)PDB

The (M)PDB can be used to promote the vertical and horizontal load spreading desired in front-to-side impacts as discussed above. As shown in Figure 2.5, the deformation pattern in the (M)PDB could be used to predict vehicle behaviour in a side impact. There has been no activity to correlate the (M)PDB results for the SUV used in the side impact simulations and tests as presented in Section 4.2. Section 3.3 mentions that the (M)PDB has no validated compatibility metrics assigned to the barrier deformation. A metric based on the slope of the barrier deformations appears to be promising and can be used in future applications to promote better horizontal load spreading and avoid the local intrusions shown in Figure 4.3. Similar metrics for vertical load spreading would also encourage this component of compatibility. Therefore the presumed influence on the (M)PDB test on vehicle front structures would be to improve vertical and horizontal load spreading. The benefits for side impact will be found from performance criteria that encourage the vertical load spreading that engages the sill and horizontal load spreading that eliminate local deformations when stiff longitudinal structures penetrate the softer side areas of the vehicle. Initial estimates of the benefit of a combined PDB/FW test are presented in FIMCAR Deliverable D1.2 [Edwards 2013] and show the benefit of an additional metric for horizontal load spreading that the FWDB test cannot provide.

4.5 Summary

The introduction of new frontal impact compatibility criteria in FIMCAR will have some limited benefit in side impacts if manufacturers use the vertical load spreading options for the FWDB. There is a risk that the encouragement of structural alignment in Rows 3&4 can lead to preferred loading high on the vehicle side. There are no horizontal load spreading requirements proposed in the FIMCAR recommendations so there will not be any explicit encouragement of stiffer horizontal crossbeams nor punishment for developing weak crossbeams. The use of a FWDB will limit the sub-optimisation potential available in a FWRB where high contact loads on limited cells can be used to meet the target row loads.

There is a weak possibility that vertical load spreading could improve with the introduction of a FWDB test. It is still beneficial in side impacts if structures have loads in Rows 3&4 compared to vehicles which have their structure located even higher (Row 5&6). The future inclusion of a (M)PDB would permit greater control of load spreading that benefits side impact.

The recommendation of FIMCAR to combine the current ODB with a full width test will balance any tendencies of vehicles to develop overly stiff frontal structures with the offset test because the full width test should encourage longer and gentler ride down behaviour. The combination of full width and offset tests will thus balance each other and not introduce worse conditions that currently observed for side impact.

5 IMPLICATIONS FOR IMPACTS WITH HEAVY GOODS VEHICLES

5.1 Review of Current Status of HGV-Car Impacts

The main issues for passenger vehicle crashes into Heavy Goods Vehicles (HGV) are addressed in UN-ECE Regulations 58 and 93 for Rear and Front Underrun protection systems (RUPs and FUPs), respectively. Both specify geometric and structural requirements for devices fitted to HGVs and their trailers to reduce the risk of passenger cars underriding the larger frame elements of the HGV chassis.

For FUPs, the guard structure can have a maximum ground clearance of 400 mm on an unladen vehicle and the corresponding value is 550 for rear guard structures. Both have requirements for a minimum vertical section height to ensure there is a reaction surface for impacting vehicles to react against.

Structural adequacy of the underrun guards is controlled by point loads that are applied to specific locations. These loads are well under the peak deformation loads of cars and are activated by even small vehicles. Krusper and Thomson investigated FUP force levels in [Krusper 2008/1, Krusper 2010]. One observation from accident analysis [Krusper 2008/2] was that the point loads for the FUP did not always resist overriding and that the lateral load spreading of the FUP was often poor on the outboard sections.

5.2 Changes Expected from FWDB

The FWDB metric will encourage car structures above 400 mm which is the maximum for FUP but not for a RUP. Thus frontal impacts can be expected to improve due to better alignment of car and truck structures. Vehicles currently designed with lower front structures will be encouraged to raise the main structures to be aligned with the FUP interaction area.

Horizontal load spreading for a passenger car would be beneficial if the FUP or RUP exhibits poor load spreading. Many real world cases involve small overlap and horizontal load spreading would be a benefit for these cases too. The FW tests do not offer incentives for improving horizontal load spreading.

SUVs and LTVs, that have been designed with higher main structures than passenger cars, could run the risk of overriding the FUP on trucks. These higher vehicles will be required to incorporate structures below their main longitudinals or, alternatively, redesign the front longitudinals to be more in line with the interaction area between 400 and 500 mm.

RUPs are currently higher than desirable for most M1 vehicles. The maximum ground clearance of 550 mm is over the main interaction area defined for the FWDB although the actual area of measurement on the FWDB is up to 580 mm due to the load cell resolution. The upper border of Row 4 will become a new constraint for vehicle designers and this may encourage structures that were above 580 mm to be lowered to apply loads in Row 4 and thus insure the vehicle crash loads are credited in the assessment. This can allow for some better alignment of structures in the case of rear impacts into HGVs. Modification to the RUP requirements are preferred, as the current RUP designs are too high to engage the structures of most cars. Car-to-truck rear impact conditions are made even worse when pre-impact braking and the resulting vehicle pitch introduces even more vertical offset between the RUP and car bumpers.

5.3 Changes Expected from ODB

The current ODB does not have any mechanism to encourage better alignment of car structures with HGVs. The maintenance of a strong occupant compartment is needed and accident data from Germany [Thompson 2013] highlights the need for good self protection and compartment stability in impacts with HGVs.

5.4 Changes due to (M)PDB

The (M)PDB metrics are currently proposed to encourage horizontal load spreading within the same vertical area as the FWDB. Current development of a deformation metric can incorporate an appropriate assessment area to encourage the vertical load spreading needed for both FUP and RUP interactions. The addition of horizontal load spreading from a (M)PDB metric would enhance the vertical load spreading and structural alignment contributed by the FWDB. An added possibility with the MPDB is increased self protection of smaller vehicles than would be possible with a fixed barrier test. The MPDB trolley mass will create a higher impact severity for all vehicles below 1500 kg and can be used to promote better safety for smaller vehicles when they collide with HGVs. The current standard for M1 vehicles only addresses the severity level for a single vehicle collision but not for a heavier collision partner vehicle. The current impact severity for (M)PDB vehicles with a mass over 1500 is not fully resolved and there is a possibility that these occupants of these vehicles can have higher injury risks.

5.5 Summary

The new FIMCAR frontal impact procedure will provide opportunities for better structural interaction between passenger cars and HGVs. There are no function based requirements in Europe that will encourage better structural alignment between passenger cars and trucks. As shown in this section, there are challenges to encourage vehicles to be aligned with RUPs and this may be better addressed through modification of the RUP requirements.

The current FUP and RUP structures are not mandated with sufficient energy and force capacity for impact severities that are encountered on the roads. There is evidence that the structural capacity of FUPs were not sufficient to prevent overriding in some collisions [Krusper 2008/1, Krusper 2010].

6 IMPLICATIONS FOR IMPACTS WITH ROAD INFRASTRUCTURE

6.1 Review of Current Status of Car-to-Road Infrastructure Impacts

The testing of roadside equipment is prescribed in Europe by standards developed by CEN TC226. These standards describe CE marking requirements for construction products which will control the sale of construction products in Europe. Guardrail and crash cushions are regulated by EN 1317 while vertical structures (poles, sign posts) are covered under EN 12767. Both of these test standards incorporate crash tests of different size vehicles with different speeds and angles, when appropriate.

Parallel to Europe, guidelines have been developed in the US which describe crashworthiness requirements for roadside equipment. The latest document describing test conditions is the Manual for Assessing Safety Hardware (MASH) [AASHTO 2009]. The US does not have formal regulations but requires MASH approved devices on roads that are part of the National Highway System. As a result, all new roadside safety devices are essentially designed to MASH requirements.

In both Europe and the US, roadside hardware is designed for impacts with a set of reference vehicles. In Europe, passenger vehicles of 800 and 1500 kg are used to represent passenger cars while in the US an 1100 car and 2240 kg pickup truck are used. Test speeds range from 70 to 110 km/h depending on the application and impact angles will vary from head on (0 deg) impacts to a maximum oblique impact angle of 20 or 25 degrees in Europe or US, respectively.

Two main issues for roadside equipment and the safety of vehicle passengers is the stiffness and structural interaction between cars and horizontal structures like guardrails. Figure 6.1 shows the geometry of vehicle structures compared to the main horizontal elements in guardrails. It is important for harmonisation that the requirements for roadside equipment do not diverge for the US and European market. FIMCAR has adopted the US definition of a common interaction zone and this will allow for better geometrical designs for vehicles and roadside equipment internationally.

The influence of vehicle stiffness is not so well understood in Guardrail Impacts. Wu et al [Wu 2004] showed that the lateral stiffness of vehicles should not be too low as this could lead to higher injury risks. Unfortunately only the US frontal impact requirement FMVSS 208 has any true oblique impact element although this situation is seldom tested in US quality control testing.

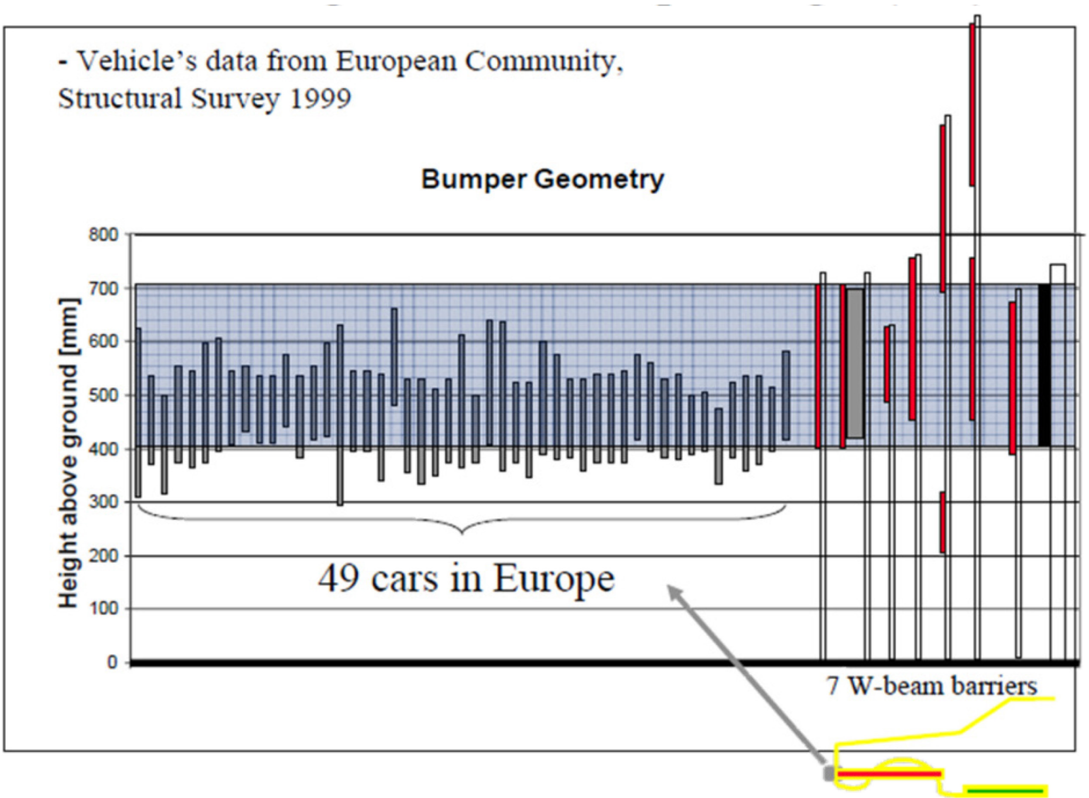

Figure 6.1: Vehicle Structures and Typical Guardrail Geometries [Wu 2003].

6.2 Changes expected from FWDB

The FWDB offers manufacturers of both vehicles and roadside hardware to identify common interaction zones where structures should interact. This would be addressed by the structural alignment metric in Rows 3&4. The FWDB will not address the issues corner impacts to the structure due to the load conditions in the FWDB.

Road equipment with narrower vertical elements increases the demands on horizontal structures in the vehicle. Strong bumper crossbeams would be desirable to reduce intrusion of the occupant compartment. The RISER project noted that impacts with narrow roadside objects were associated with more fatal accidents and that many of these fatalities could be attributed to intrusion into the occupant compartment [Naing 2008]. The FWDB has not been found suitable for developing horizontal load spreading metrics to address this issue.

6.3 Changes expected from ODB

The current ODB is not expected to change vehicle designs to be more suitable for roadside collisions than what they are currently. The offset loading condition requires some bending resistance in the vehicle front but there are no new metrics that are going to encourage more robust structures with the current offset protocol.

Alignment of frontal structures is somewhat encouraged by the bumper element on the ODB. However the FWDB will actively control this feature in vehicles.

6.4 Changes due to MPDB

The MPDB has already been identified as a potential tool for encouraging load spreading in vehicle frontal designs. If a suitable metric is defined, horizontal load spreading could then be better incorporated into vehicle structures. The horizontal load spreading metric could also be envisioned to provide wider front structures that improve the corner impacts of the vehicle with structures like guardrails.

6.5 Summary

The main benefits of the FIMCAR frontal impact assessment approach are to encourage structural alignment of vehicle and road infrastructure. The main benefits would be realised in the FWDB test where vertical vehicle geometry is actively assessed and controlled. The new requirements will be an important input for road designers to ensure that future systems are built to known structural architectures in vehicles.

7 DISCUSSION

The influence of the candidate test procedures and assessment procedures on other impact types has been presented. The common theme is the potential to structurally align vehicle components with the opposing structures. In some cases like truck RUPs, requirements of the collision partner are not ideal for passenger vehicle designs. Introduction of performance requirements that harmonise geometric alignment will support future harmonisation of crashworthiness designs, independent of type of passenger cars.

The final assessment approach that was developed within the FIMCAR project duration does not have a horizontal load spreading assessment. The FWDB was not suitable for this procedure and validated (M)PDB deformation metric for load spreading in the vertical and horizontal directions is still in the final stages of development. Preferably, a load spreading metric could be introduced into a future offset test like the (M)PDB. The load spreading metric would address many impact conditions identified in impacts with vehicle sides, HGVs, and roadside equipment. The benefits of stepwise implementation of the FWDB and (M)PDB assessment criteria on frontal impacts is presented in FIMCAR Deliverable D1.2 [Edwards 2013] and shows that structural alignment, provided by the FWDB, only addresses part of the safety issue.

Stiffness issues with current vehicle designs are not expected to be affected negatively by the FIMCAR approach. The combination of a FWDB and ODB will create a balanced frontal stiffness that cannot be expected to be softer than vehicle side structures, nor stiffer than HGV frames. Current compartment strength needs to be maintained and the frontal stiffness can be tuned to appropriate levels through the ODB test and A-pillar performance as well as the dummy criteria.

In total no negative side effect resulting from the FIMCAR assessment approach is expected. However, not all potential for improvements of other impact types is exploited following the lack of load spreading assessment.

8 CONCLUSIONS

The current test candidates and final assessment procedure selected by FIMCAR do not have any obvious negative implications for side impacts, HGV impacts, nor impacts with road equipment. The worst case scenario is that the introduction of a FW metric with minimum load requirements in Rows 3&4 can lead to single point -optimisation and worsened horizontal load spreading that may manifest itself in other impact configurations. This risk is small and the selection of a FWDB will likely mitigate this side effect. The deformable barrier dampens the peak loads and introduces a need to have larger contact surfaces to generate sufficient loads in the assessment area.

The current assessment approach in FIMCAR may introduce limited improvements for these investigated collisions, but it is expected that the harmonisation of interaction areas will allow a convergence to compatible structural designs in the road and traffic network.

GLOSSARY

EEVC:	European Enhanced Vehicle Safety Committee
EEVC WG13	EEVC Working Group on Side Impact
EEVC WG15	EEVC Working Group on Frontal Impact Compatibility
Euro NCAP:	European New Car Assessment Programme
FUP:	Front Underrun Protection device of HGV
FW:	Full Width Frontal Impact test
FWDB	Full Width Deformable Barrier test
FWRB	Full Width Rigid Barrier test
HGV:	Heavy Goods Vehicle
IIHS:	US Insurance Institute
LCW:	Load Cell Wall
MDB:	Movable Deformable Barrier test
MPDB:	Movable Deformable Barrier test using the PDB barrier face
NHTSA:	US National Highway Traffic Safety Administration
ODB:	Off-set Deformable test (used for current ECE R94)
Part 581 zone:	Bumper zone according to FMVSS Part 581 Bumper Standard
PEAS:	Primary Energy Absorbing Structures
PDB:	Progressive Deformable Barrier test (50% offset frontal impact test)
Row 3:	3rd Row of an LCW from bottom (i.e., ranging from 330 to 455 mm)
Row 4:	4th Row of an LCW from bottom (i.e., ranging from 455 to 580 mm)
RUP:	Rear Underrun Protection device of HGV
SEAS:	Secondary Energy Absorbing Structures
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility
VRU:	Vulnerable road user (typically pedestrians, cyclists, motorcyclists)

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SEVENTH FRAMEWORK PROGRAMME

FIMCAR
XIII – Cost Benefit Analysis

FIMCAR
frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

Although the number of road accident casualties in Europe is falling the problem still remains substantial. In 2011 there were still over 30,000 road accident fatalities [EC 2012]. Approximately half of these were car occupants and about 60 percent of these occurred in frontal impacts. The next stage to improve a car's safety performance in frontal impacts is to improve its compatibility for car-to-car impacts and for collisions against objects and HGVs. Compatibility consists of improving both a car's self and partner protection in a manner such that there is good interaction with the collision partner and the impact energy is absorbed in the car's frontal structures in a controlled way which results in a reduction of injuries. Over the last ten years much research has been performed which has found that there are four main factors related to a car's compatibility [Edwards 2003, Edwards 2007]. These are structural interaction potential, frontal force matching, compartment strength and the compartment deceleration pulse and related restraint system performance.

The objective of the FIMCAR FP7 EC-project was to develop an assessment approach suitable for regulatory application to control a car's frontal impact and compatibility crash performance and perform an associated cost benefit analysis for its implementation.

This deliverable reports the cost benefit analysis performed to estimate the effect of the following potential changes to the frontal impact regulation:

- Option 1 – No change and allow current measures to propagate throughout the vehicle fleet.
- Option 2 – Add a full width (FW) test to the current offset Deformable Barrier (ODB) test.
- Option 3 – Add a full width test (FW) and replace the current ODB test with a Progressive Deformable Barrier (PDB) test.

The following conclusions were made:

- For the benefit analysis it was assumed that the introduction of a full-width test with appropriate compatibility and dummy metrics has the potential to address the frontal impact issues under/override related to structural alignment and restraint related acceleration type injuries. Limited potential of the full width test was expected for addressing fork effect issues. It was also assumed that the replacement of the ODB by the PDB/MPDB test procedure with an appropriate homogeneity metric had the potential to address the frontal impact issues under/override related to vertical load spreading, fork effect and low overlap as well as frontal force matching/compartment strength.
- The benefits of three potential changes to the frontal impact regulation were calculated for GB and Germany and scaled to give an indicative estimate for Europe.
  - For Option 1 'No change', a small benefit of about 2.0% or less of all car occupant Killed and Seriously Injured (KSI) casualties was estimated;
  - For Option 2 'Add FW test: Benefit of 5% to 12% of all car occupant KSI casualties was estimated. It was shown that this benefit consisted of:
    - Structural alignment (under/override related to structural alignment): 0.3% - 0.8%. However, it should be noted that the benefit related to structural alignment was likely to be under-estimated.
    - Restraint system: (restraint related deceleration related injuries): 5% - 11%

  - For Option 3 ‘Add FW test and replace ODB test with PDB test’ 9% to 14% of all car occupant KSI casualties.
  - Note: Benefit percentages for Options 2 and 3 do not include the benefit of Option 1 ’No change’.
- Break-even costs for options 2 and 3 were calculated. Comparison of these costs with costs estimated by previous projects indicated that the monetary value of the benefits of implementing Option 2 should be greater than the costs to modify the cars for restraint system changes. However, further work is needed to determine precisely what changes would be needed to deliver the injury reduction assumed for the benefit analysis and precisely what test configuration (in particular dummies) and performance limits would be needed to enforce these changes.

The following points should be noted:

- The benefit was calculated assuming the implementation of complete assessment procedures. However, appropriate dummy assessment values and dummy selection were not addressed by FIMCAR and appropriate PDB/MPDB metrics are not yet established.
- Possible further potential benefits from the definition of a common interaction zone related to truck underrun protection and roadside guard rails were not considered in the study.

1 INTRODUCTION

1.1 FIMCAR Project

Although the number of road accident casualties in Europe is falling the problem still remains substantial. In 2011 there were still over 30,000 road accident fatalities [EC 2012]. Approximately half of these were car occupants and about 60 percent of these occurred in frontal impacts. The next stage to improve a car's safety performance in frontal impacts is to improve its compatibility for car-to-car impacts and for collisions against objects and HGVs. Compatibility consists of improving both a car's self and partner protection in a manner such that there is good interaction with the collision partner and the impact energy is absorbed in the car's frontal structures in a controlled way which results in a reduction of injuries. Over the last ten years much research has been performed which has found that there are four main factors related to a car's compatibility [Edwards 2003, Edwards 2007]. These are structural interaction potential, frontal force matching, compartment strength and the compartment deceleration pulse and related restraint system performance.

The objective of the FIMCAR FP7 EC-project was to develop an assessment approach suitable for regulatory application to control a car's frontal impact and compatibility crash performance and perform an associated cost benefit analysis for its implementation.

Within the FIMCAR project off-set, full overlap and MDB test and assessment procedures were developed further with the ultimate aim to propose a compatibility assessment approach. This should be accepted by a majority of the involved industry and research organisations. The development work will be accompanied by harmonisation activities to include research results from outside the FIMCAR consortium and to disseminate the project results early, taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work Package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The main objective of the work for this deliverable was:

- Determine the benefits and costs of improved frontal impact compatibility for the following options:
  - Option 1: No change, i.e. progression to baseline
    - Baseline is defined to be a vehicle fleet in which all vehicles have safety performance level that is at least equivalent to that required to be UNECE Regulation 94 compliant. Legislation mandates that all new types of cars registered post 1st Oct 1998 shall be Regulation 94 compliant and all cars registered post 1st Oct 2003 shall be Regulation 94 compliant. It should be noted that the safety performance levels of many of these vehicles will be much higher than that required by Regulation 94 because of the influence of programmes such as Euro NCAP.
  - Option 2: Add Full Width (Deformable Barrier) test

  - Option 3: Add Full Width test and replace the current Offset deformable Barrier (ODB) test with a Progressive Deformable Barrier (PDB) test.

Specific objectives were:

- Benefits
  - Identify casualty target populations for GB and Germany
  - Estimate benefits for GB and Germany and convert into a monetary value
  - Scale to give indicative estimate for Europe
- Costs
  - Derive 'break-even' costs per vehicle and compare with cost estimates from previous projects

Note: 'Break-even' costs are the costs when there is a cost to benefit ratio of one and are calculated by converting the benefit into a monetary value and dividing this value by the number of new cars registered annually.

It should be noted that some additional analyses were performed for GB to estimate:

- Benefit of Option 1 'No change' for casualties in side impacts.
- Target population of casualties in car struck on the side for car-to-car side impacts in which the side impact compatibility of the striking car has been improved.
- Benefits of different variants of Option 3, e.g. a PDB test that only addressed the fork effect structural interaction instead of all of the structural interaction issues, i.e. over/underride, fork effect and low overlap.

1.3 Structure of this Deliverable

This deliverable starts with a description of the approach followed for this study. It then describes the accident databases used. This is followed by sections describing the benefit analyses performed for GB, Germany and Europe, respectively. The next section describes the cost analysis. The final section summarises the conclusions of the study.

2 APPROACH

The overall approach was that separate analyses were performed to estimate the benefits for Great Britain (GB) and Germany (D) for each option. These results were scaled to give an indicative estimate of the benefits for Europe. Break-even costs per car i.e. a cost benefit ratio of one, were calculated by converting the benefit into a monetary value using published casualty costs for fatal, serious and slight injuries and dividing this value by the number of new cars registered annually. These costs were compared with costs calculated in previous projects such as VC-COMPAT [Cuerden 2006] and APROSYS [Edwards 2008] for other potential regulatory changes related to car crash compatibility. These steps are described in greater detail in the bullet points below:

- Estimate benefit of Option 1 'No change' to get to baseline which is the starting point for the estimate of the benefit of future changes
- Estimate target populations and benefits for Options 2 & 3 for GB and Germany and scale to give indicative estimate for Europe.
    - Both national and detailed accident databases were used for this work. National data will be used to determine high level information such as the number of car occupant casualties in frontal impacts. Detailed data will be used to obtain sufficient information to be able to estimate what level of injury reduction, if any, the casualty would experience if the potential regulatory changes being investigated were made.
- Convert benefits into monetary values using government published values for preventing, fatal, serious and slightly injured road accident casualties, calculate break-even costs and compare with cost estimates from previous projects such as:
    - VC-COMPAT FP5 project
    - APROSYS FP6 project.
    - EEVC WG13/21 costs and benefits study for improved side impact.

To ensure that the results were appropriate for use to identify compatibility issues in the current fleet and help develop changes to the current legislation (UN-ECE Regulation 94) as far as was possible only Regulation 94 compliant vehicles (or those with an equivalent safety level) were selected for this work. The legal situation for frontal impact type approval within the European Union is:

- Since 1 October 1998 the Frontal Impact Directive 96/79/EC (equivalent to Regulation 94) was mandated for type approval of new vehicle types within the European Union.
- Since 1 October 2003 an approval was mandated for the first registration of a vehicle.

As a result of 96/79/EC, all vehicles in the fleet registered since 1st October 2003 are Regulation 94 compliant and vehicles registered before this date may not be compliant. However, many vehicles registered between 1st Oct 1998 and 1st Oct 2003 may be compliant. In the accident data vehicle registration year information is available. Hence, this parameter was used to help select Regulation 94 compliant vehicles. The precise details of how this was achieved are given in following sections for each of the accident databases analysed.

Because of differences between the accident databases, slightly different methodologies were used for the GB and German benefit analyses. However, the spirit of the methodologies was kept as similar as possible. The accident databases, both methodologies and associated results are described in the sections below.

3 DESCRIPTION OF ACCIDENT DATABASES

A description of the accident databases used for this work is given below.

3.1 Great Britain

3.1.1 STATS19 National Accident Statistics

STATS19 data is comprised of the details of road traffic accidents attended by the police in Great Britain. In theory the police are required to attend every road traffic accident that involves an injury and whilst on scene officers fill out a series of standard forms. Details of the nature of the accident, the location, a crude classification of injuries and the overall accident severity are all collected. Officers make a judgement, often without further information from hospitals, and record the severity of the injured casualties and the overall accident as 'slight', 'serious' or 'killed'. This data is then collected, collated and analysed by the UK Department for Transport (DfT).

STATS19 is, in principle, the national database in which all traffic accidents that result in injury to at least one person are recorded, although it is acknowledged that some injury accidents are missing from the database and a few non-injury accidents are included. The database primarily records information regarding where the accident took place, when the accident occurred, the conditions at the time and location of the accident, details of the vehicles involved and information about the casualties. Approximately 50 pieces of information are collected for each accident [RRCGB 2010].

The severity of the casualties involved in the accident is assessed by the investigating police officer. Each casualty is recorded as being either slightly, seriously, or fatally injured. Fatal injury includes only casualties who died less than 30 days after the accident, not including suicides or death from natural causes. Serious injury includes casualties who were admitted to hospital as an in-patient. Slight injury includes minor cuts, bruises, and whiplash. The full definitions of these injury severities (and all other information recorded in STATS19) are given in the STATS20 document which accompanies the STATS19 form. These definitions are also available online at www.stats19.org.uk. Accidents that are recorded in STATS19 are summarised annually in the DfT "Reported Road Casualties Great Britain" (RRCGB) series.

Data for accidents from 2008 to 2010 inclusively were used for this analysis.

3.1.2 CCIS Detailed Accident Database

The Co-operative Crash Injury Study (CCIS) collected in-depth real world crash data from 1983 to 2010. Vehicle examinations were undertaken at recovery garages several days after the collision. Car occupant injury information was collected from hospitals and questionnaires sent to survivors. Multi-disciplinary teams examined crashed vehicles and correlated their findings with the injuries the victims suffered to determine how the car occupants were injured. The objective of the study was to improve car crash performance by developing a scientific knowledge base, which has been used to identify the future priorities for vehicle safety design as changes take place.

Accidents were investigated according to a stratified sampling procedure, which favoured cars containing fatal or seriously injured occupants as defined by the British Government definitions of fatal, serious and slight. In order for an accident to be included in the study, a "newer" car must have been involved – one that was 7 years old or younger at the time of the accident. CCIS data collected from June 2000 to March 2010 were used for this study.

The stratified sampling procedure means that CCIS records a relatively large number of fatal and serious accidents, which are often the most interesting from an injury prevention point of view.

CCIS data from phases 7 and 8, which encompass accidents collected from June 2000 to March 2010, were used for this analysis.

3.2 Germany

3.2.1 German National Accident Statistics

The statistical recording of all police reported traffic accidents in Germany is reported in the national statistics hosted by the German Federal Statistical Office. Survey records for the statistics of road traffic accidents are the copies of the standard traffic accident notices as used for the entire Federal Republic which are completed by the police officers attending the accident. After its transfer to data recording media, the information included in the accident notices is tabulated on a monthly and annual basis at the statistical offices at the states according to a standard programme for the entire Federal Republic. The state results are compiled to the federal result.

Data for accidents from 2005 to 2007 inclusively were used for this analysis.

3.2.2 GIDAS

GIDAS (German In-Depth Accident Study) is the largest and most comprehensive in-depth road accident study in Germany. Since mid 1999, the GIDAS project investigates about 2000 accidents in the areas of Hanover and Dresden per year and records up to 3000 variables per crash. The project is supported by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT) [Otte 2003].

In GIDAS, road traffic accidents involving personal injury are investigated according to a statistical sampling process using the "on the scene" approach. That means, teams are called promptly after the occurrence of any kind of road traffic accident with at least one injured person which occurred in determined time shifts. Along with this method, severe accidents are recorded slightly more frequently than accidents with lower injury severities and this is mainly caused by a lower notification rate or late information. In order to avoid such biases in the database and to approach regional and national representativeness, comparisons are made regularly with the official accident statistics and e.g. the investigation areas were chosen accordingly to the national road network and built-up areas.

The detailed documentation of the accidents is performed by survey teams consisting of specialised students, technical and medical staff. The data scope includes technical vehicle data, crash information, road design, active and passive safety systems, accident scene details and cause of the accident. Surveyed factors include impact contact points of passengers or vulnerable road users, environmental conditions, information on traffic control and other parties (road users) involved. Additionally, vehicles are measured more in detail, further medical information is gathered and an extensive crash reconstruction is performed.

Data for accidents from 2000 to 2010 inclusively were used for this analysis.

3.3 European CARE Database

CARE contains basic data on all accidents as collected by most EU member states, i.e. data from national databases.

Data from 2008 were used for this analysis or nearest preceding year if not available.

4 GB ANALYSIS

This study used STATS19 data from road traffic accidents that occurred in the years 2008 to 2010 inclusive. It also used CCIS data from phases 7 and 8, which includes accidents collected from 2001 to 2010. Using the STATS19 data the numbers of fatally injured and seriously injured occupants by 'user type' and year are summarised in Table 1 and illustrated in Figure 4.1. Figure 4.1 also shows the breakdown of impact types (frontal, side or other) for fatally injured and seriously injured car users.

Table 1: STATS19 (national data) road accident casualties

User type	Number of fatalities				Number of seriously injured			
	2008	2009	2010	Average	2008	2009	2010	Average
Car users	1,257	1059	835	1050	10,711	10053	8914	9893
	50%	48%	45%	47%	41%	41%	39%	40%
Pedestrians	572	500	405	492	6070	5545	5200	5605
	23%	23%	22%	22%	23%	22%	23%	23%
Pedal cyclists	115	104	111	110	2450	2606	2660	2572
	5%	5%	6%	5%	9%	11%	12%	11%
Motorcycle users	493	472	403	456	5556	5350	4780	5229
	19%	21%	22%	21%	21%	22%	21%	21%
Bus / coach users	6	14	9	10	426	356	392	391
	0%	1%	0%	0%	2%	1%	2%	2%
Other users	95	73	87	85	821	780	714	772
	4%	3%	5%	4%	3%	3%	3%	3%
Total	2,538	2,222	1,850	2,203	26,034	24,690	22,660	24,461
	100%	100%	100%	100%	100%	100%	100%	100%

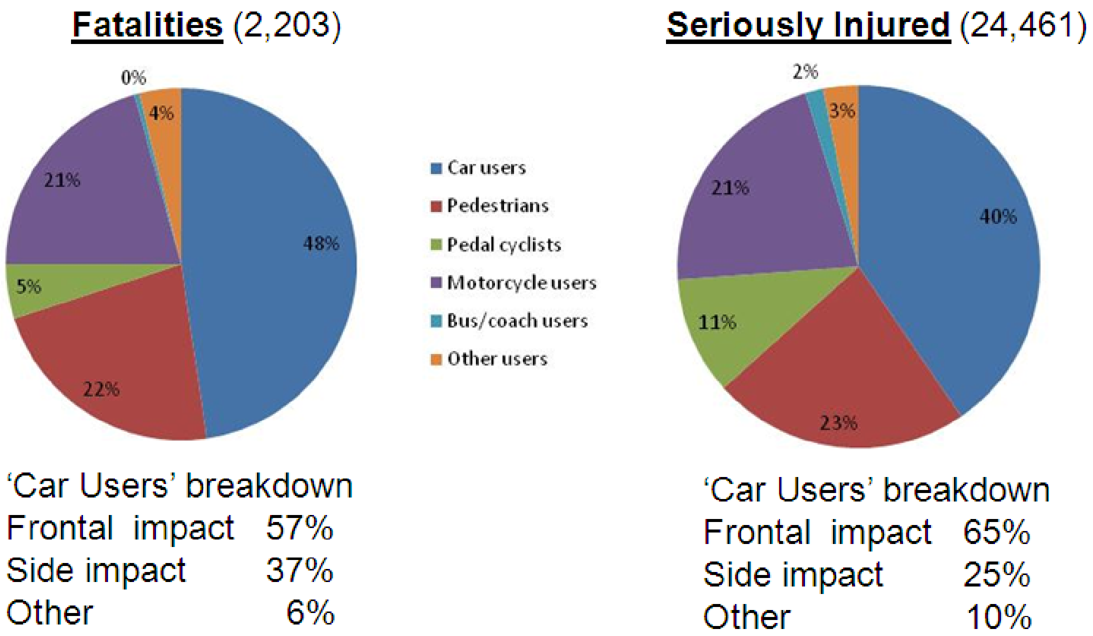


Figure 4.1: STATS19 (national data) road accident casualties (average 2008-2010).

4.1 Benefit of Option 1 'No change'

Only STATS19 national data from 2008 to 2010 inclusive was used for this part of the analysis. The benefit of this option arises from the natural replacement of old vehicles in the fleet which are not regulatory compliant with new vehicles which are regulatory compliant and may also have much higher safety performance levels as encouraged by Euro NCAP.

The legal situation for frontal impact within the European Union is:

- Since 1st October 1998: all new types of car are mandated to be Regulation 94/95 compliant.
- Since 1st October 2003: all cars are mandated to be Regulation 94/95 compliant.

Two types of analyses were undertaken. Both analyses were based on the assumption that the total number of casualties (killed plus seriously injured plus slightly injured will remain the same) but with newer vehicles the distribution will change. Firstly a simple proportion analysis was performed. Following this, a regression analysis was performed to remove some of the confounding factors present in the proportional analysis that may incorrectly influence the results such as older people drive newer cars.

Both analyses were performed for frontal and for side impacts for comparison.

4.1.1 Proportion Analysis

4.1.1.1 Methodology

The following methodology was used:

- Calculate distribution of car occupant casualties in frontal /side impacts for cars of all ages
  - Proportion of killed, seriously injured, slightly injured
- Calculate distribution of car occupant casualties in frontal/side impacts in Regulatory compliant / Euro NCAP-influenced cars, i.e. cars registered 1st Oct 2003 or later

– 1st Oct 1998 – all new types of car R94 / 95 compliant
– 1st Oct 2003 – all cars registered R94 / 95 compliant

- Estimate benefit of renewal of vehicle fleet by assuming that number of casualties remains the same and injury distribution changes to that for cars registered 1st Oct 2003 or later

4.1.1.2 Results

Frontal Impacts

The distribution of car occupant casualties in frontal impacts in all ages of cars average per year (2008-2010) by impact partner is shown in Table 2.

Table 2: Distribution of car occupant casualties in frontal impacts in all ages of cars average per year (2008-2010).

Impact type	Car occupant injury severity			Total
	Killed	Seriously injured	Slightly injured	
Car to Car front	137 0.80%	1727 10.11%	15215 89.09%	17,079 100.00%
Car to Car side/rear	21 0.12%	841 4.93%	16195 94.95%	17,057 100.00%
Car to HGV/PSV	65 2.97%	288 13.16%	1,835 83.87%	2,188 100.00%
Car to LGV	18 0.87%	194 9.34%	1,864 89.79%	2,076 100.00%
Car to Object	207 1.53%	1855 13.68%	11497 84.79%	13,559 100.00%
Car / Multiple (3+ vehicles)	113 1.02%	1,037 9.35%	9,939 89.63%	11,089 100.00%
Car to Other/Unknown	39 0.81%	475 9.88%	4291.3 89.30%	4,805 100.00%
Total	600 0.88%	6,417 9.46%	60,836 89.66%	67,853 100.00%

The distribution of car occupant casualties in frontal impacts in new cars (i.e. those registered after 1st Oct 2003) average per year (2008-2010) by impact partner is shown in Table 3.

Table 3: Distribution of car occupant casualties in frontal impacts in new cars average per year (2008-2010).

Impact type	Car occupant injury severity			Total
	Killed	Seriously injured	Slightly injured	
Car to Car front	23 1.06%	218 10.05%	1928 88.89%	2,169 100.00%
Car to Car side/rear	3 0.12%	119 4.88%	2317 95.00%	2,439 100.00%
Car to HGV/PSV	20 2.81%	83 11.67%	608 85.51%	711 100.00%
Car to LGV	3 0.43%	65 9.29%	632 90.29%	700 100.00%
Car to Object	65 1.55%	568 13.55%	3559 84.90%	4,192 100.00%
Car / Multiple (3+ vehicles)	33 0.83%	339 8.50%	3,615 90.67%	3,987 100.00%
Car to Other/Unknown	10 0.78%	127 9.93%	1142 89.29%	1,279 100.00%
Total	157 1.01%	1,519 9.81%	13,801 89.17%	15,477 100.00%

Application of the proportions for casualty distribution for new cars to all cars gives an estimate of the number of casualties in frontal impacts in all cars average per year (2008-2010) assuming all cars have crashworthiness performance of new cars as shown in.Table 4

Table 4: Estimate of car occupant casualties in all ages of cars assuming all cars have crashworthiness performance of new cars.

Impact type	Car occupant injury severity			Total
	Killed	Seriously injured	Slightly injured	
Car to Car front	181 1.06%	1717 10.05%	15181 88.89%	17,079 100.00%
Car to Car side/rear	21 0.12%	832 4.88%	16204 95.00%	17,057 100.00%
Car to HGV/PSV	62 2.81%	255 11.67%	1871 85.51%	2,188 100.00%
Car to LGV	9 0.43%	193 9.29%	1874 90.29%	2,076 100.00%
Car to Object	210 1.55%	1837 13.55%	11512 84.90%	13,559 100.00%
Car / Multiple (3+ vehicles)	92 0.83%	943 8.50%	10054 90.67%	11,089 100.00%
Car to Other/Unknown	38 0.78%	477 9.93%	4291 89.29%	4,805 100.00%
Total	612 1.01%	6254 9.81%	60987 89.17%	67853 100.00%

The benefit was calculated by differencing the number of casualties in Table 4 and Table 2 (Table 5).It is interesting to note that overall and in particular for car front to car front impacts an increase in the number of fatalities is estimated. This result is unexpected and may be caused by confounding factors and hence is one of the reasons that a regression analysis was performed to try and remove the effect of some of these factors.

Table 5: Benefit of Option 1 'No change' for frontal impacts, expressed in casualties per year, note that a negative number represents a disbenefit, i.e. an increase in casualties.

Impact type	Car occupant injury severity			Total
	Killed	Seriously injured	Slightly injured	
Car to Car front	-44	10	34	0
Car to Car side/rear	0	9	-9	0
Car to HGV/PSV	3	33	-36	0
Car to LGV	9	1	-10	0
Car to Object	-3	18	-15	0
Car / Multiple (3+ vehicles)	21	94	-115	0
Car to Other/Unknown	1	-2	1	0
Total	-12	163	-151	0

Side Impacts

A similar process was followed as for frontal impacts to give the following results.

Table 6: Distribution of car occupant casualties in side impacts in all ages of cars average per year (2008-2010).

Impact type	Car occupant injury severity			Total
	Killed	Seriously injured	Slightly injured	
Car to Car front	181 1.06%	1717 10.05%	15181 88.89%	17,079 100.00%
Car to Car side/rear	21 0.12%	832 4.88%	16204 95.00%	17,057 100.00%
Car to HGV/PSV	62 2.81%	255 11.67%	1871 85.51%	2,188 100.00%
Car to LGV	9 0.43%	193 9.29%	1874 90.29%	2,076 100.00%
Car to Object	210 1.55%	1837 13.55%	11512 84.90%	13,559 100.00%
Car / Multiple (3+ vehicles)	92 0.83%	943 8.50%	10054 90.67%	11,089 100.00%
Car to Other/Unknown	38 0.78%	477 9.93%	4291 89.29%	4,805 100.00%
Total	612 1.01%	6254 9.81%	60987 89.17%	67853 100.00%

Table 7: Distribution of car occupant casualties in side impacts in new cars average per year (2008-2010).

	Car occupant injury severity			
Impact type	**Killed**	**Seriously injured**	**Slightly injured**	**Total**
Car to Car front	11 0.64%	90 5.24%	1616 94.12%	1,717 100.00%
Car to Car side/rear	2 0.21%	45 4.79%	892 94.99%	939 100.00%
Car to HGV/PSV	11 1.19%	45 4.88%	866 93.93%	922 100.00%
Car to LGV	5 0.97%	27 5.21%	486 93.82%	518 100.00%
Car to Object	42 2.92%	215 14.95%	1181 82.13%	1,438 100.00%
Car / Multiple (3+ vehicles)	16 1.17%	90 6.58%	1,261 92.25%	1,367 100.00%
Car to Other/Unknown	8 0.95%	63 7.46%	774 91.60%	845 100.00%
Total	95 1.23%	575 7.42%	7,076 91.35%	7,746 100.00%

Table 8: Benefit of Option 1 'No change' for frontal impacts, expressed in casualties per year.

	Car occupant injury severity			
Impact type	**Killed**	**Seriously injured**	**Slightly injured**	**Total**
Car to Car front	19	36	-54	0
Car to Car side/rear	0	-30	29	0
Car to HGV/PSV	6	22	-28	0
Car to LGV	1	18	-19	0
Car to Object	1	62	-63	0
Car / Multiple (3+ vehicles)	9	41	-49	0
Car to Other/Unknown	-1	34	-34	0
Total	35	184	-219	0

It is interesting to note that in contrast to frontal impacts an overall decrease in killed casualties (i.e. a benefit) was predicted for side impacts.

4.1.2 Regression Analysis

4.1.2.1 Methodology

As with the proportional analysis above, this analysis was based on the assumption that the total number of casualties (i.e. fatal plus serious plus slight) in a 'regulatory compliant / Euro NCAP influenced' fleet would be the same as in the current fleet, but the proportion of fatal, serious and slight casualties would be different. This effectively assumes that 'regulatory compliant / Euro NCAP influenced' cars have the same accident configurations as cars that are not 'regulatory compliant / Euro NCAP influenced'. It should be noted that primary safety features such as Electronic Stability Control (ESC) may alter the configurations of the accidents that cars have. This could be a confounding factor in the analysis performed which was not controlled for because appropriate data were not available to do this.

Regression modelling was used to determine the influence of the car's registration period on the casualty's injury severity for the different accident types, e.g. car-to-car accidents, car-to-object accidents etc. whilst taking into account confounding factors such as occupant age, gender and vehicle type. The analysis was most complex for car-to-car accidents because the registration period and type of both cars involved needed to be taken into account. The explanatory variables used were:

Type of the car	Minis/superminis', 'Small saloons', 'Medium saloons', 'Large saloons', Luxury saloons', 'Sports cars', '4x4s/MPVs', 'Taxis(black cabs)'
Registration period of the car	'to 12/93', '1/94 to 9/98', '10/98 to 9/03', 'from 10/03' and 'not known'
Driver age/sex	(male, female) x (0-25, 26-60, 61-99) and age or sex 'not known'

A Generalised Linear Model was fitted to the relationship:

$$\frac{K(i,j,k,l,m)}{C(i,j,k,l,m)} = \alpha(i).\beta(j).\gamma(k).\delta(l).\varepsilon(m) \qquad (1)$$

where $C(i,j,k,l,m)$= number of drivers of age/sex i of cars of type j and registration period k who are injured in collisions with cars of type l and registration period m

$K(i,j,k,l,m)$= number of these injured drivers who were killed or seriously injured

$\alpha, \beta, \gamma, \delta, \varepsilon$ are coefficients to be estimated

As K/C is a proportion, it was appropriate to fit model (1) using the logistic regression facility of the Generalised Linear Interactive Modelling (GLIM) programme [Francis 1993]. The GLIM programme requires a 'reference level' for each explanatory variable. The estimated coefficients show the effects for the other levels relative to the effect for this level, also the statistical significance of any differences. The benefit of changing to a 'regulatory compliant / Euro NCAP influenced' fleet was estimated from the effect of change in the car's registration period on the casualty outcome, whilst keeping all other factors such as casualty age and gender constant.

4.1.2.2 Results

Car-to-Car Accidents

Exploratory analyses were made of the casualty data from car-to-car accidents grouped according to the registration periods of the driver's car and the other car. These demonstrated the improvement in secondary safety in the car fleet: drivers of the older ('to 9/98' or pre-Directive) cars were more likely to be killed or seriously injured than drivers of newer ('from 10/03' or post-Directive) cars. It was also clear that the severity of the driver injuries was greater when in collision with a newer car than an older car, i.e. the newer cars were more aggressive.

Section 4.1.2.1 introduced the logistic regression analysis that can be used to identify the effects of registration period upon casualty severity, independent of the effects of the other variables such as car type. The results of this analysis that relate to registration period are presented in Table 9.

Table 9: Influence of registration period on driver casualty severity in car-car accidents, estimates from GLIM models.

Impact			killed / all casualties proportion	t	serious casualties / all casualties proportion	t
Front	Driver's car	to 12/93	1.04%	1.76	10.1%	1.69
		1/94 to 9/98	0.65%		8.8%	
		10/98 to 9/03	0.39%	-3.06	7.4%	-4.14
		from 10/03	0.44%	-2.26	6.8%	-5.68
	Other car	to 12/93	0.82%	0.61	8.5%	-0.32
		1/94 to 9/98	0.65%		8.8%	
		10/98 to 9/03	0.53%	-1.05	8.6%	-0.39
		from 10/03	0.85%	1.48	9.8%	2.43
Side	Driver's car	to 12/93	0.33%	-1.22	7.0%	1.80
		1/94 to 9/98	0.68%		5.3%	
		10/98 to 9/03	0.60%	-0.56	4.5%	-2.15
		from 10/03	0.37%	-2.75	4.2%	-3.00
	Other car	to 12/93	0.76%	0.22	6.2%	0.92
		1/94 to 9/98	0.68%		5.3%	
		10/98 to 9/03	0.89%	1.05	5.8%	1.15
		from 10/03	1.21%	2.34	5.9%	1.23

Estimates refer to reference levels for driver age and sex (men aged 0 - 25), for car type (Minis and Superminis) and for registration period (1/94 to 9/98)

The results output by the GLIM software from a logistic regression model can be tricky to interpret, so they have been illustrated using the reference level selected for the modelling, i.e. the table shows the proportions estimated by the fitted models for male drivers aged 0 - 25 of Minis and Superminis who were injured in frontal impacts with other Minis and Superminis. With the 'driver's car' results, the other car is taken to be of 'to 9/98' registration; with the 'other car' results, the driver's car is taken to be of 'to 9/98' registration. If other groups were selected for the illustration then the levels would differ but the relationship would not; the t-values would be unaffected. The Table shows that both casualty proportions are significantly lower when the driver's car is 'from 10/03' than when it is '1/94 to 9/98' in both frontal and side impacts.

The effect is reversed with respect to the other car, although it does not achieve significance some cases.

These results conform to the general trends seen in the exploratory analysis, and the trends for killed and serious casualties are similar. They do not show, however, the overall trade-off between the increase in aggressivity shown by the increased other car proportions for 'from 10/03' cars and the improvement of secondary safety shown by the reduced driver's car proportions for 'from 10/03' cars. This can be evaluated by considering in turn the groups of car-to-car accidents in the data set used to fit (1). When a car (driver's or other) is not from the 'from 10/03' registration period, the coefficients from the GLIM model are used to calculate the severity proportion that would be expected if it had been 'from 10/03'. This simulates the casualty outcome if the same set of accidents had occurred, but all cars had the characteristics of modern (from 10/03) cars. All GLIM coefficients are used, irrespective of their t-values.

Table 10 presents the results, which are not national figures but relate to the subset of data that is used to fit the GLIM models. This includes only driver casualties in accidents where the details of both cars and both drivers are known. These account for 69% of fatal casualties, 65% of serious casualties and 68% of slight casualties. The 'model' data are the values fitted by the regression model to the actual casualty data. The 'alternative' data show the changes to the 'model' data when the effects of changing to 'from 10/03' cars are simulated. Consider the column headed 'from 10/03' which shows the effects for drivers of modern cars; these cars are unchanged in the simulation but the cars with which they collide generally become more aggressive so the casualty numbers tend to increase. The 'from 10/03' rows, by contrast, show the effects of unchanged aggressivity of these new cars but improved secondary safety in the cars that they hit.

Table 10: Estimated driver casualty changes in frontal impacts if all cars had been regulatory compliant (from 10/03).

	Other car		**Driver's car**				
			to 12/93	**1/94 to 9/98**	**10/98 to 9/03**	**from 10/03**	**all**
Frontal impacts							
Killed	to 12/93	model	0.8	2.2	2.7	2.3	8
		alternative	0.4	1.6	3.1	2.4	7
	1/94 to 9/98	model	3.1	11.7	13.4	12.8	41
		alternative	1.8	10.5	19.8	16.7	49
	10/98 to 9/03	model	4.8	19.3	24.1	22.8	71
		alternative	3.3	21.2	43.9	36.6	105
	from 10/03	model	9.3	31.8	41.9	42.1	125
		alternative	4.0	21.7	47.6	42.1	115
	all	model	18	65	82	80	245
		alternative	9	55	114	98	277
Serious casualties	to 12/93	model	5	21	35	27	88
		alternative	2	4	19	38	31
	1/94 to 9/98	model	27	148	240	191	605
		alternative	20	128	248	214	610
	10/98 to 9/03	model	51	299	527	422	1,299
		alternative	39	265	555	481	1,340
	from 10/03	model	64	341	635	523	1,562
		alternative	43	265	588	523	1,419
	all	model	146	809	1,436	1,163	3,554
		alternative	106	677	1,429	1,249	3,461
Side impacts							
Killed	to 12/93	model	0.1	0.9	1.9	1.1	4
		alternative	0.2	0.8	1.8	1.7	5
	1/94 to 9/98	model	0.4	4.7	9.7	5.1	20
		alternative	0.9	4.6	10.6	9.2	25
	10/98 to 9/03	model	1.1	13.0	27.2	15.6	57
		alternative	1.7	9.7	22.6	21.3	55
	from 10/03	model	1.3	19.3	40.1	23.2	84
		alternative	1.5	10.6	24.5	23.2	60
	all	model	3	38	79	45	165
		alternative	4	26	60	55	145
Serious casualties	to 12/93	model	3	8	16	13	41
		alternative	2	2	6	15	13
	1/94 to 9/98	model	10	45	89	74	218
		alternative	7	39	92	82	219
	10/98 to 9/03	model	20	101	208	186	516
		alternative	12	81	196	188	476
	from 10/03	model	17	100	205	191	514
		alternative	11	80	191	191	473
	all	model	51	254	519	465	1,289
		alternative	32	206	493	473	1,203

These estimates relate to the subset of the national data used for the GLIM models, i.e. those accidents for which details of both cars and both drivers are known.

Overall, it is estimated that if all cars had had the characteristics of modern cars, the number of drivers killed in car-to-car frontal impacts between 2008 and 2010 would have been 13% greater, 277 rather than 245; 12% fewer would have been killed in side impacts, 145 rather than 165. The number of serious casualties in frontal impacts would have been 3% less, 3,461 rather than 3,554, and in side impacts the number would have been 7% less, 1,203 rather than 1,289.

Single car accidents

This section considers driver casualties in frontal and side impacts that involve a single car and no other vehicle, irrespective of what objects might have been hit on or off the carriageway. The appropriate GLIM model is a simplified version of (1) as only details of one vehicle are included, and Table 11 is the equivalent of Table 9 for single vehicle accidents. There is a small reduction of the casualty proportions among modern cars that achieves statistical significance in one case.

Table 11: Influence of registration period on driver casualty severity in single car accidents, estimates from GLIM models.

Impact		killed / all casualties proportion	t	serious casualties / all casualties proportion	t
Front	to 12/93	1.46%	0.35	16.6%	1.94
	1/94 to 9/98	1.32%		14.0%	
	10/98 to 9/03	1.34%	0.07	13.6%	-0.73
	from 10/03	1.10%	-1.29	13.1%	-1.52
Side	to 12/93	4.07%	0.11	19.6%	0.57
	1/94 to 9/98	3.94%		18.2%	
	10/98 to 9/03	2.68%	-2.43	16.1%	-1.99
	from 10/03	3.15%	-1.34	15.1%	-2.71

Estimates refer to reference levels for driver age and sex (men aged 0-25), for car type (Minis and Superminis) and for registration period (1/94 to 9/98)

Table 12 now simulates the casualty outcome if the same set of accidents had occurred in 2008-10 but all cars had the characteristics of regulatory compliant (from 10/03) cars. The net effect is a small reduction in killed and serious casualties. Overall, it is estimated that if all cars had had the characteristics of modern cars, 49 fewer drivers would have been killed in single car frontal impacts between 2008 and 2010, a 12% reduction; the net effect is nil in side impacts. The number who were seriously injured would have reduced by 4% in frontal impacts and 8% in side impacts.

Table 12: Estimated casualty changes in single car accidents if all cars had been regulatory compliant.

Impact			Driver's car to 12/93	1/94 to 9/98	10/98 to 9/03	from 10/03	all
Front	Killed	model	16.0	87.0	176.1	120.1	399
		alternative	12.1	72.5	145.3	120.1	350
	Serious casualties	model	131	704	1,434	1,092	3,362
		alternative	103	657	1,380	1,092	3,233
Side	Killed	model	13.0	67.0	94.0	76.0	250
		alternative	10.1	53.6	110.4	76.0	250
	Serious casualties	model	60	314	598	397	1,369
		alternative	46	260	562	397	1,265

These estimates relate to the subset of the national data used for the GLIM models, i.e. those accidents for which details of the car and the driver are known

These analyses have grouped together all casualties in single car accidents irrespective of the objects hit. They have been repeated with a subset of casualties, those whose cars hit an object off the carriageway (i.e. cases with 'first object hit off the carriageway'=none were excluded). It is estimated that if all cars were modern then, based on those accidents for which details of the car and the driver are known:

- the number of drivers killed would fall from 358 to 309 in frontal impacts and from 234 to 223 in side impacts
- the number of drivers seriously injured would fall from 2,813 to 2,732 in frontal impacts and from 1,157 to 1,091 in side impacts

Car-to-other Vehicle Accidents

Far fewer drivers were injured in accidents that involved one car and one other vehicle that was not a car than in the previous two groups of accidents, but it was still possible to separate the analysis by type of other vehicle. The analysis was restricted to accidents between cars and those vehicle groups that are appreciably heavier than cars: buses, coaches and goods vehicles. These accidents account for 11% of car drivers injured in frontal impacts involving two vehicles, but 33% of car drivers killed. 'Other vehicle' refers in the remainder of this section to these types of heavier vehicle.

The appropriate GLIM model is a simplified version of (1) as the type of the other vehicle is known but not its registration period. The diagnostic statistics confirm the importance of treating the four types of other vehicle separately. The results are presented in Table 13, which is the equivalent of Table 9 with the additional reference level of other vehicle=bus or coach. The results show a small reduction of the fatality proportion among modern cars in frontal impacts that does not achieve statistical significance and a larger reduction of the serious casualty proportion that does. This tends to suggest that the reduction of the fatality proportion is real, but does not appear to be significant because of the relatively small numbers. The reduction in side impacts did not achieve statistical significance.

Table 13: Influence of registration period on driver casualty severity in car-other vehicle accidents, estimates from GLIM models.

Impact		killed all casualties proportion	t	serious casualties all casualties Proportion	t
Front	to 12/93	0.95%	-0.65	21.5%	2.77
	1/94 to 9/98	1.35%		14.3%	
	10/98 to 9/03	1.62%	0.81	11.6%	-2.40
	from 10/03	1.07%	-0.97	11.3%	-2.59
Side	to 12/93	2.83%	-0.11	14.3%	1.32
	1/94 to 9/98	3.04%		10.2%	
	10/98 to 9/03	2.70%	-0.43	10.2%	0.00
	from 10/03	2.14%	-1.20	8.5%	-1.36

Estimates refer to reference levels for driver age and sex (men aged 0 - 25), for car type (Minis and Superminis), for registration period (1/94 to 9/98) and for other vehicle (bus or coach)

Table 14 now simulates the casualty outcome if the same set of accidents had occurred in 2008 - 2010 but all cars had the characteristics of regulatory compliant (from 10/03) cars. The net effect is a reduction in fatal and serious casualties. Overall, it is estimated that if all cars had had the characteristics of regulatory compliant cars, 29 (20%) fewer drivers would have been killed in car-to-other vehicle frontal impacts between 2008 and 2010, and the number who were seriously injured would have reduced by 9%. 14 (16%) fewer drivers would have been killed in side impacts and 50 (12%) would have been seriously injured.

These casualty reductions may be offset slightly by increased casualty numbers in the other vehicles as a result of the increased aggressivity of regulatory compliant cars that was identified above for car-to-car accidents, but a complementary data set for the casualties in these other vehicles would be needed to analyse this.

Table 14: Estimated casualty changes if all cars had been regulatory compliant, car-to-other vehicle accidents.

Impact			Driver's car				
			to 12/93	1/94 to 9/98	10/98 to 9/03	from 10/03	all
Front	Killed	model	4.0	28.0	71.0	45.0	148
		alternative	4.5	22.2	47.1	45.0	119
	Serious	model	49	183	307	262	801
	casualties	alternative	26	145	299	262	732
Side	Killed	model	3.0	19.0	38.0	30.0	90
		alternative	2.3	13.4	30.2	30.0	76
	Serious	model	16	74	177	141	408
	casualties	alternative	9	61	146	141	358

These estimates relate to the subset of the national data used for the GLIM models, i.e. those accidents for which details of the car and its driver are known

Adjustment and Disaggregation

The previous sections have estimated the number of fatal and serious casualties in 2008 - 2010 for three groups of accident under the 'from 10/03' scenario, namely that all of the cars involved had the characteristics of the 'from 10/03' registration group. These estimates will now be combined to estimate changes to national casualty totals.

The first step is to adjust the earlier estimates to make allowance for the driver casualties that were excluded when the GLIM models were fitted, i.e. those with incomplete details. Adjustment factors are calculated for each of the three datasets by comparing the number of casualties with complete details and the total number. Table 15 presents the results. The final 'Total' column is the sum of the three 'Adjusted estimate' columns.

Table 15: Adjustment of driver casualty estimates.

Impact			Accidents involve:						
			Single car		Two cars		One car, one other vehicle		
			Estimate from Table 12	Adjusted estimate	Estimate from Table 10	Adjusted estimate	Estimate from Table 14	Adjusted estimate	Total
Front	Killed	model	399	481	245	364	148	178	1,023
		alternative	350	422	277	411	119	143	976
	Serious	model	3,362	4,055	3,554	5,274	801	963	10,291
	casualties	alternative	3,233	3,899	3,461	5,136	732	880	9,915
Side	Killed	model	250	301	165	249	90	107	658
		alternative	250	301	145	219	76	91	611
	Serious	model	1,369	1,651	1,289	1,945	408	486	4,082
	casualties	alternative	1,265	1,525	1,203	1,815	358	427	3,767
Adjustment factor									
	Front		1.206		1.484		1.202		
	Side		1.206		1.509		1.192		

The estimates from the Total column were adjusted to take account of casualties in the accidents not included in sections above, principally those that involve three or more vehicles but also those that involve one car and one lighter vehicle. It would in principle be possible to make a basic analysis of these casualties similar to that for single car accidents but these data were not extracted. Instead, it was assumed that the effects will be a weighted mean of the effects of the three groups that have been studied. The results are shown in

Table 16, and indicate that if all cars in 2008-2010 had been to the 'from 10/03' standard then the number of car driver casualties would have been slightly reduced, 4.5% fewer fatalities and 3.7% fewer serious casualties.

Table 16: Final car driver casualty estimates, frontal impacts, 2008-2010.

Impact			Estimate from Table 15	Adjustment factor to allow for excluded accidents	Final estimate	Reduction
Front	Killed	model	1,023	1.233	1,261	
		alternative	976		1,204	4.5%
	Serious casualties	model	10,291	1.218	12,692	
		alternative	9,915		12,228	3.7%
Side	Killed	model	658	1.233	811	
		alternative	611		753	7.1%
	Serious casualties	model	4,082	1.218	5,034	
		alternative	3,767		4,646	7.7%

For the purposes of more detailed analyses required for this project, some of the results presented above need to be disaggregated. Firstly, the car-to-car results from Table 10 are split according to whether the first point of impact on the other car was frontal or side/rear. Separate sets of accident records have been extracted and GLIM models fitted as for the car-to-car accidents above

Table 17: Disaggregate casualty estimates, car-car accidents.

Impact			Other car hit on: front	side/rear	sum	all	Difference
Front	Killed	Model	198	24	222	245	9%
		Alternative	242	22	264	277	4%
		Reduction	-22%	8%	-19%	-13%	
	Serious casualties	Model	2,391	1,080	3,471	3,554	2%
		Alternative	2,332	1,096	3,428	3,461	1%
		Reduction	2%	-1%	1%	3%	
Side	Killed	Model	138	15	153	165	7%
		Alternative	121	17	138	145	5%
		Reduction	12%	-14%	10%	12%	
	Serious casualties	Model	877	376	1253	1289	3%
		Alternative	807	367	1174	1203	2%
		Reduction	8%	2%	6%	7%	

Note: a negative reduction is an increase

The fact that the first point of impact is sometimes recorded as 'did not impact' or 'not known' means that the sum of the two sets of estimates is slightly less than the earlier set. Table 17 compares the disaggregated results with the overall results from Table 10 (shown as 'all').

Next, the casualty reduction estimates in car-to-other vehicle accidents from

Table 14 are disaggregated. There are too few casualties involving the remaining groups of 'other vehicles' for analysis.

Table 18: Disaggregate casualty estimates, car-other vehicle accidents.

Impact			Other vehicle: Bus or coach	Van	HGV	All
Front	Killed	Model	14	33	101	148
		alternative	11	26	81	119
		Reduction	20%	20%	19%	20%
	Serious casualties	Model	103	333	365	801
		alternative	93	303	335	732
		Reduction	9%	9%	8%	9%
Side	Killed	Model	11	25	54	90
		alternative	9	21	46	76
		Reduction	16%	16%	16%	16%
	Serious casualties	Model	61	160	187	408
		alternative	53	141	164	358
		Reduction	13%	12%	12%	12%

Table 19: Final disaggregate car driver casualty estimates, frontal and side impacts, 2008-2010.

Impact		Killed			Serious casualties		
		model	alternative	reduction	model	alternative	reduction
Front	Car to car front	294	359	-22%	3,548	3,460	2%
	Car to car side/rear	36	33	8%	1,603	1,627	-1%
	Car to PSV/HGV	138	111	20%	563	515	8%
	Car to van	40	32	20%	400	365	9%
	Car to object (sva)	432	373	14%	3,393	3,295	3%
	Multiple-vehicle	237	229	3%	2,010	1958	3%
	Total	1,176	1,137	3%	9,507	9,262	3%
Side	Car to car front	208	182	12%	1,323	1,218	8%
	Car to car side/rear	23	26	-14%	567	554	2%
	Car to PSV/HGV	78	65	16%	296	259	12%
	Car to van	30	25	16%	191	168	12%
	Car to object (sva)	282	268	5%	1,396	1,315	6%
	Multiple-vehicle	156	143	9%	798	743	7%
	Total	777	710	9%	4,570	4,256	7%

Note: a negative reduction is an increase

The results from both these tables need to be adjusted to allow for the sampling in the GLIM data, and Table 19 makes these adjustments. Casualties in multiple-vehicle accidents have been included in the table although there has been no GLIM analysis for this casualty group.

The estimates were prepared as for Table 15, on the assumption that the effects will be a weighted mean of the effects of the groups that have been analysed.

Calculated benefits for frontal and side impact casualties are summarised in Table 20.

Table 20: Summary of benefits predicted by regression analysis for car occupant casualties in frontal and side impacts.

Benefit of Option 1, 'No change'	% (No.) of car occupant casualties	
	Killed	Seriously injured
Car occupant frontal impact casualties	2.0% (21)	1.7% (164)
Car occupant side impact casualties	3.1% (32)	1.7% (171)

4.1.3 Summary of Conclusions

- Frontal impact
  - Regression analysis estimates a benefit of 2.0% (21) of killed and 1.7% (164) of seriously injured car occupant casualties
  - However, for the car-to-car frontal impact subset both proportional and regression analyses show that the number of fatal casualties increases with newer cars. This may indicate that the increased self-protection of cars is being offset by their increased aggressivity.
- Side impact
  - Regression analysis estimates a benefit of 3.1% (32) of killed and 1.7% (171) of seriously injured car occupant casualties
  - For the car-to-car side impact subset both the proportional and regression analyses show that the number of fatal casualties decreases with newer (regulatory compliant / EuroNCAP influenced) cars.

4.2 Benefit of Option 2 'Add Full Width test' and Option 3 'Add Full Width Test and Replace Current ODB Test with PDB Test'

4.2.1 Methodology

The five-step methodology described below was used to estimate target populations and benefits for Options 2 and 3. The methodology uses both national data and detailed accident data because there was insufficient information in the national data to be able to estimate the benefit. Hence the detailed accident data from CCIS was used to provide the information needed to estimate the benefit for a limited number of casualties and results scaled to estimate the benefit nationally. This approach is typical for the case when detailed information about the accident is needed to estimate the benefit.

1. Start with 'baseline' national data – Casualties in regulatory compliant / Euro –NCAP influenced vehicle fleet, i.e. Option 1 'No change' baseline calculated above using regression analysis and national data
   2. Form equivalent 'baseline' dataset in detailed accident data
   3. Determine number/proportion of casualties in target population for each option
      - Remove casualties not likely to experience benefit, e.g. unbelted, etc.

   – For remaining casualties perform detailed case analysis to determine which ones likely to experience some benefit
4. Determine benefit for each casualty in target population for each option
   – Estimate injury reduction for each casualty in the target population using injury reduction model
5. Scale proportions from detailed analyses to obtain national target population and benefit

4.2.2 Representativeness of CCIS

CCIS data were examined to determine the proportion of (i) fatally injured casualties by impact partner compared with STATS19 data (Figure 4.2) and (ii) seriously injured casualties by impact partner compared with STATS19 data (Figure 4.3). This showed that HGV impacts are over-represented in CCIS and car-to-car front impacts are under-represented. To remove this bias, the analysis was performed for each impact partner type.

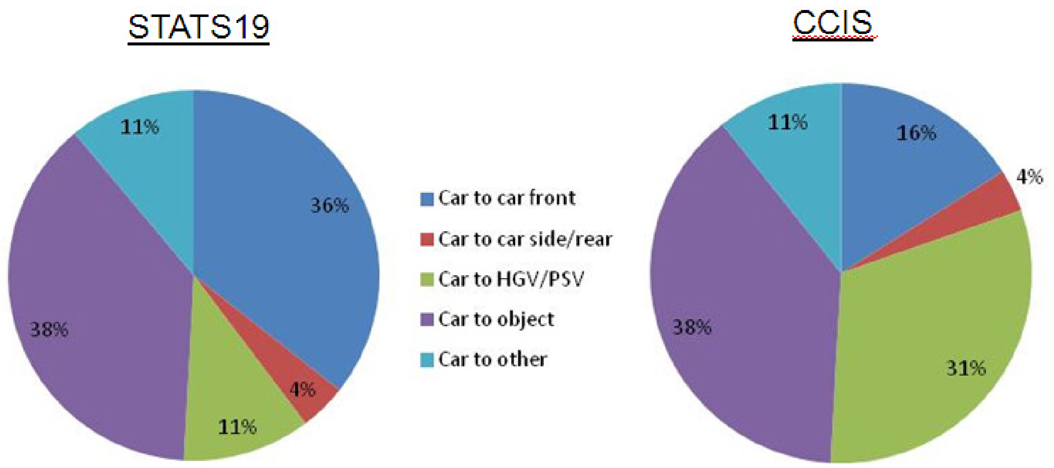


Figure 4.2: Representativeness of CCIS by impact partner (fatally injured occupants).

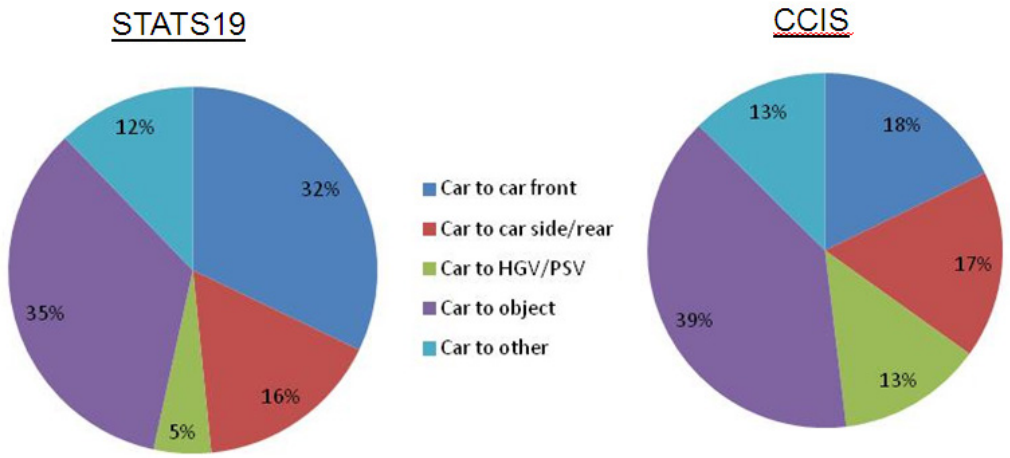


Figure 4.3: Representativeness of CCIS by impact partner (seriously injured occupants).

Secondly, CCIS data were examined to determine how representative CCIS data are of national (STATS19) data in terms of the age of (i) fatally injured occupants (Figure 4.4) and (ii) seriously injured occupants (Figure 4.5). This analysis showed a reasonable representation (although older (46-65 and >66 years of age) fatally injured occupants are slightly over-represented in CCIS and younger (12-25 years of age) fatally injured occupants are slightly under-represented). This slight bias was ignored because it was thought that it would not affect the validity of the analysis significantly.

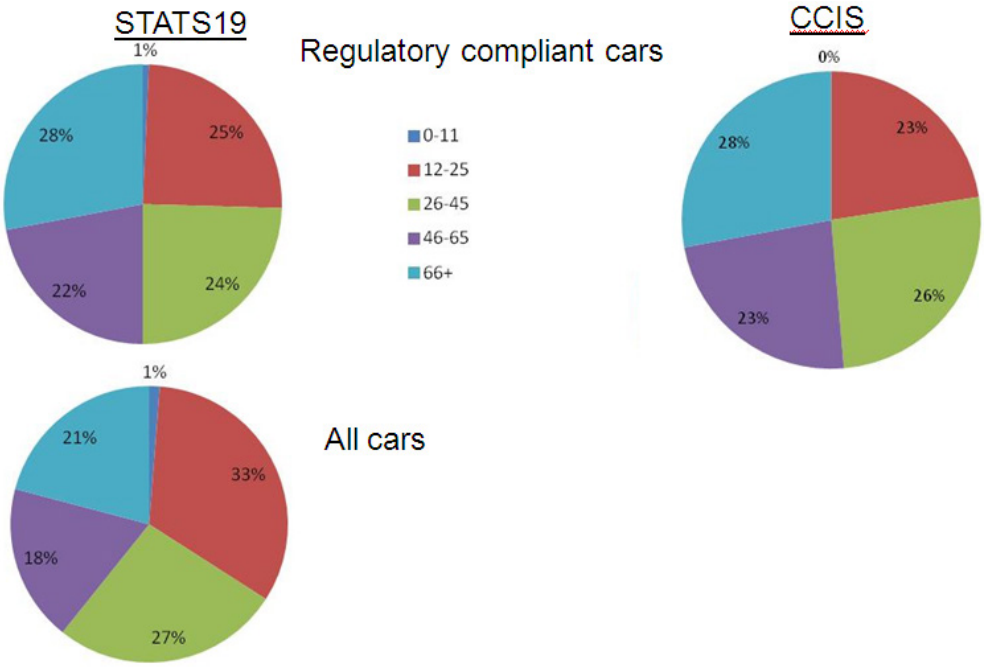


Figure 4.4: Representativeness of CCIS by age of occupant (fatally injured occupants).

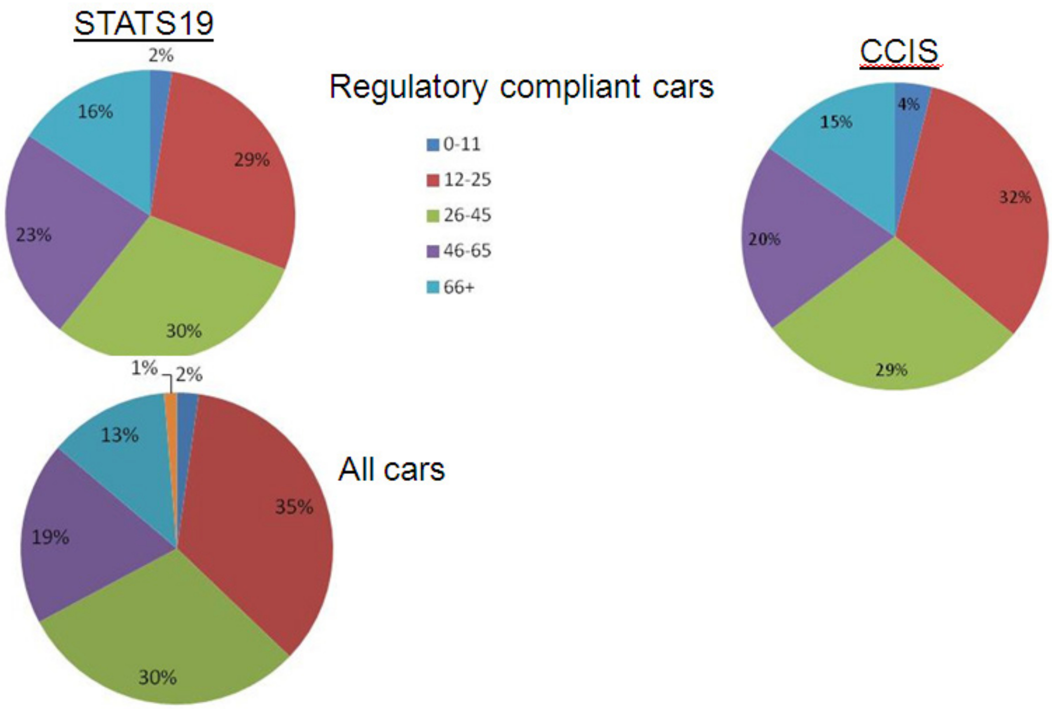


Figure 4.5: Representativeness of CCIS by age of occupant (seriously injured occupants).

4.2.3 Estimate of Target Population

<u>Baseline and formation of equivalent datasets</u>

The starting point for the analysis was the national baseline i.e. the number of casualties in frontal impacts in the regulatory compliant or Euro NCAP-influenced vehicle fleet calculated from STATS19 data. Table 21 summarises the number of fatally injured and seriously injured car occupant casualties in frontal impacts by impact partner type which was estimated as part of the work to derive the benefit of Option 1 'No change' described above.

Table 21: Road accident casualties in regulatory compliant / Euro NCAP-influenced vehicle fleet (frontal impacts).

Impact type	**Car occupant casualties**	
	Killed	**Seriously injured**
Car to car front	167	1684
Car to car side / rear	19	854
Car to HGV / PSV	52	263
Car to object	179	1801
Car to other / unknown	52	640
Car / multiple (3+ vehicles)	109	1010
Total	579	6253

Selection criteria were applied to the CCIS dataset to form equivalent CCIS baseline datasets for frontal impacts for different impact partner types. (As stated above, analysis was performed by impact partner type to remove the CCIS impact type sample bias i.e. over-estimation of HGV impacts). Cases meeting these selection criteria formed the comparison point with baseline national STATS19 data. The following criteria were applied to derive the CCIS baseline casualty datasets for frontal impacts:

- Accident occurred between 2000 and 2010 (inclusive).
- The casualty was killed or seriously injured.
- The casualty was a car occupant.
- A significant frontal impact occurred.
- The nature of the injury, the impact type and seatbelt use were all known.
- The casualty was in a regulatory compliant car or one which had an equivalent crash safety level.
    - Note: Initially to select cars that were regulatory compliant a criterion of 'those registered post 1 October 2003' was considered. However, it was found that with this approach the data sample size was not large enough to perform a meaningful analysis. Hence, the approach was modified to the one in which safety performance levels of vehicles registered between 2000 and 1st Oct 2003 were assessed further using type introduction date and Euro NCAP test data to determine whether or not they would have had a safety performance level sufficient to be regulatory compliant.

A further set of selection criteria was applied to casualties included in the CCIS baseline dataset to identify those casualties where a benefit may be achieved for the chosen options i.e. those casualties to be taken forwards for detailed analysis. For frontal impacts, the following criteria were applied:

- No rollover occurred before the first impact.
- Seatbelt was used by the casualty.
- No unbelted occupant was seated behind the casualty.

- The occupant was a front-seat occupant.

Where the above criteria were not met, it was assumed that the occupant would not experience a benefit from the measures proposed in Option 2 or Option 3. These cases were therefore excluded from the target population prior to detailed analysis. Cases meeting the above criteria were taken forwards for detailed case analysis to determine whether they should be included in the target population. The selection process for occupants in frontal impacts is illustrated in Figure 4.6.

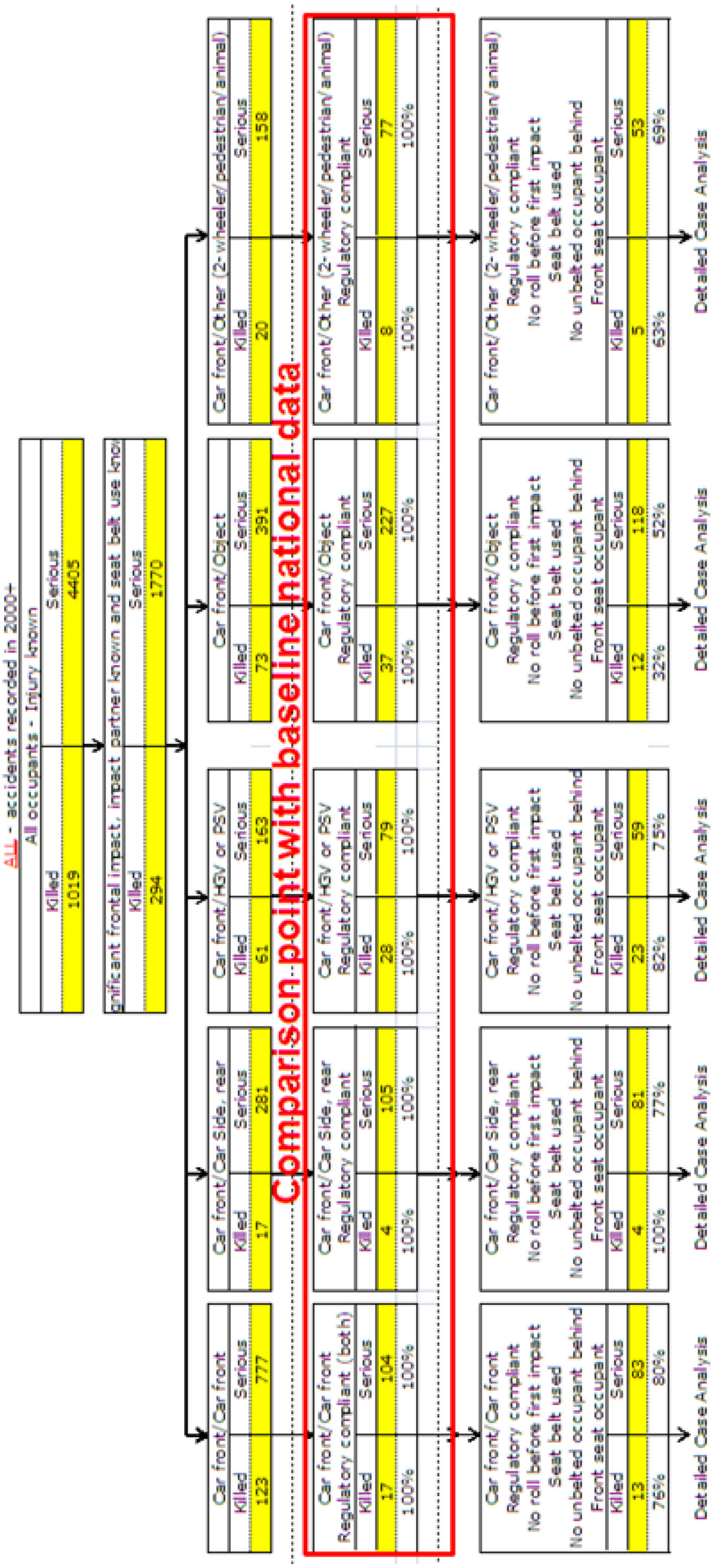


Figure 4.6: Formation of equivalent baseline CCIS dataset for frontal impacts.

Detailed Case Analysis

Detailed case analysis was undertaken for the casualties meeting all of the above criteria. This continued work started in the 'Accident analysis' task reported in FIMCAR Deliverable D1.1 [Thompson 2013]. The additional work involved a review of all cases analysed previously and the analysis of the additional cases included in the data sets used for the benefit analyses, Each case was assessed to identify (i) a structural interaction problem (over- / under-ride, fork effect, or low overlap), or (ii) a frontal force matching / compartment strength problem, or (iii) casualties with deceleration-related injuries (note: the absence of intrusion was used to help identify deceleration-related injuries). This enabled the target populations for Option 2 (full width test) and Option 3 (full width test and replace ODB with PDB test) to be identified as follows:

- Improved structural interaction (Options 2 and 3)
    - Casualties in vehicles for which a structural interaction problem has been identified.
        - Over- / under-ride – full width; PDB.
        - Fork effect – PDB.
        - Low overlap – PDB.
- Improved frontal force matching / compartment strength (Option 3)
    - Casualties in vehicles for which a frontal force matching / compartment strength problem has been identified – PDB.
- Improved restraint performance due to the introduction of the full width test (Options 2 and 3)
    - Casualties which have deceleration-related injuries in high overlap – full width.

In summary it was assumed that the introduction of a full-width test with appropriate compatibility and dummy metrics has the potential to address the frontal impact issues under/override related to structural alignment and restraint related acceleration type injuries. Limited potential of the full width test was expected for addressing fork effect issues. It was also assumed that the replacement of the ODB by the PDB/MPDB test procedure with an appropriate homogeneity metric had the potential to address the frontal impact issues under/override related to vertical load spreading, fork effect and low overlap as well as frontal force matching/compartment strength.

Each case was 'flagged' to show whether Option 2 and/or Option 3 was considered likely to provide a benefit for the occupant given the nature of the issue identified. Those casualties where a benefit was considered possible were included in the target population and taken forwards to the next stage (estimate of benefit – see section 4.2.4). Examples of the detailed case analysis are shown in Annex A.

Breakdown of the Issues Identified in the Target Population

A breakdown of the number of fatally injured or seriously injured (MAIS2+) casualties identified for each issue (overlap, fork effect or over- / under-ride) is shown in Figure 4.7. Fatally injured and seriously injured casualties are illustrated separately in Figure 4.8 and Figure 4.9 respectively. The bias in the CCIS dataset to HGV impact partner (described in section 4.2.2 above) is not taken into account in these figures. It should be noted that there was not sufficient information available for all cases to perform the detailed analysis; often there were not enough appropriate photographs to identify whether or not structural interaction problems were present. Therefore these casualties/cases were removed from the data set and the proportions used for scaling calculated from the remaining dataset. This is why the total number of casualties identified for detailed case analysis in Figure 4.6 above is greater than the total number included in the breakdown in Figure 4.7 below.

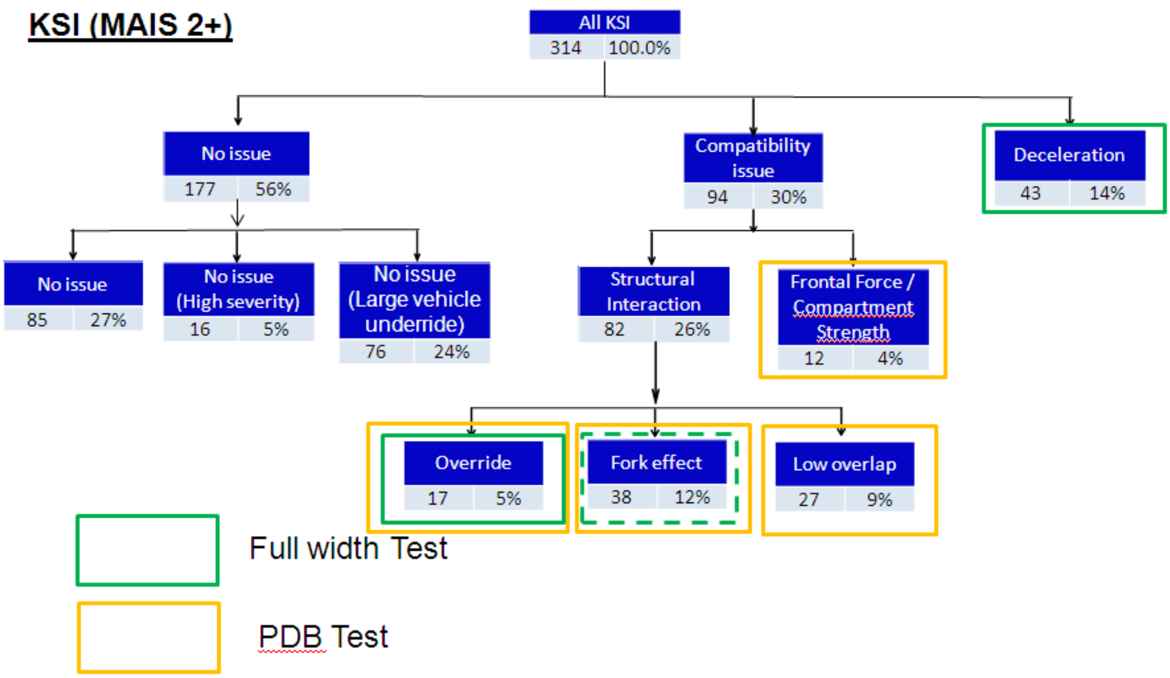


Figure 4.7: Detailed case analysis (target population) breakdown of killed or seriously injured casualties (MAIS 2+) casualties.

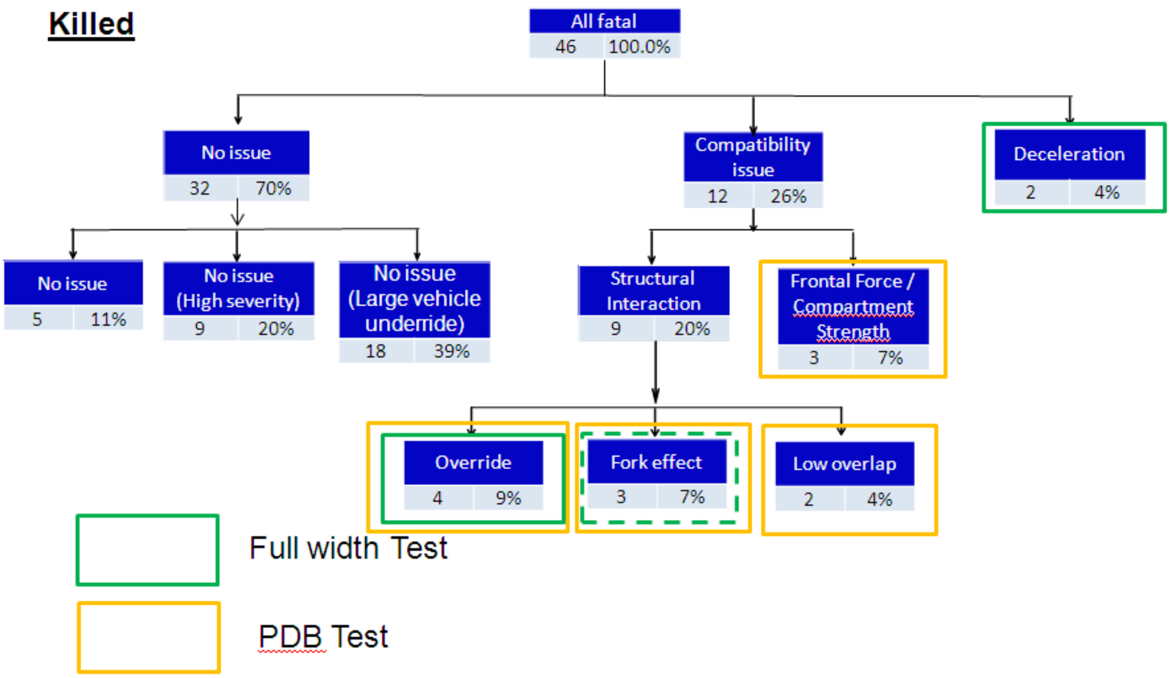


Figure 4.8: Detailed case analysis (target population) breakdown of killed casualties).

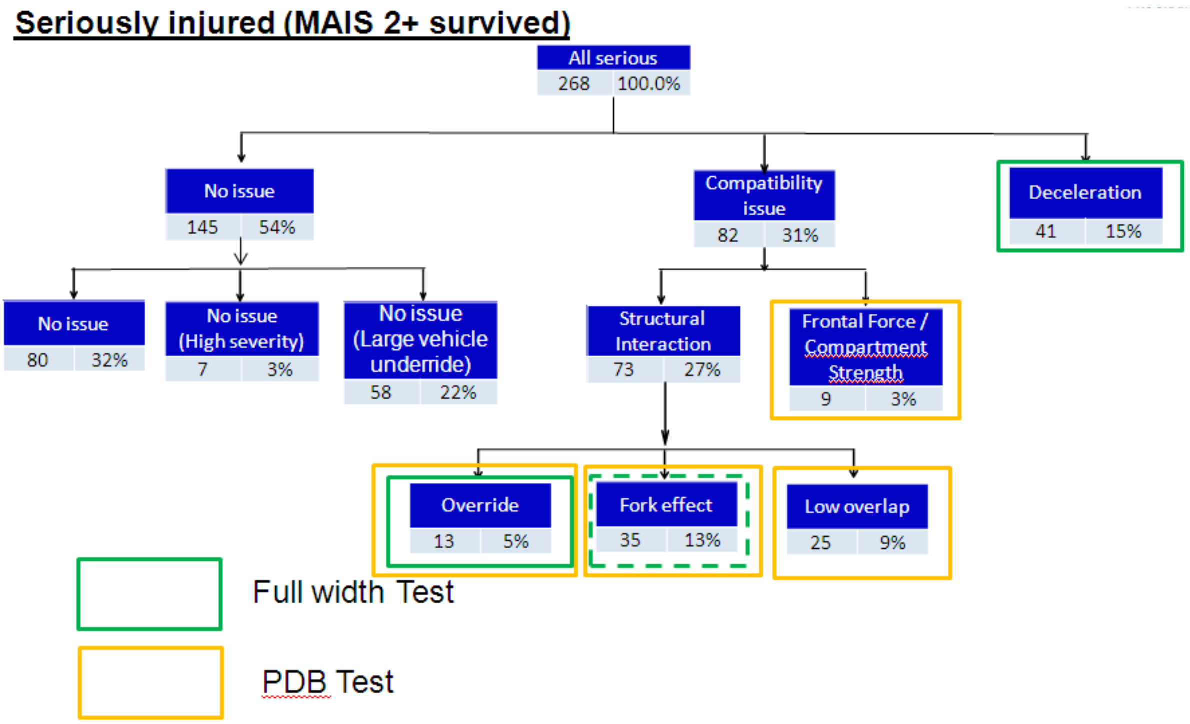


Figure 4.9: Detailed case analysis (target population) breakdown of seriously injured casualties.

<u>CCIS Proportions and Scaling to the National Dataset</u>

Table 22 shows the proportions of occupants included in the CCIS equivalent baseline datasets for whom a benefit was expected for Options 2 and 3. (Note: the proportion of casualties in the target population for the impact type 'car-to-multiple (3+ vehicles)' was calculated by estimating the number of casualties in multiple vehicle accidents in which the vehicle has a significant frontal impact and applying a weighted average of the proportions for other impact types to these casualties).

Table 22: CCIS target population proportions (frontal impacts).

Impact type	CCIS target population proportions			
	Killed		Seriously injured	
	Option 2	Option 3	Option 2	Option 3
Car-to-car front	0.353	0.529	0.436	0.499
Car-to-car side / rear	0	0	0.248	0.276
Car-to-HGV / PSV	0	0.046	0.046	0.046
Car-to-object	0.144	0.144	0.3	0.373
Car-to-other / unknown	0	0	0.098	0.147
Car /multiple (3+ vehicles)	0.072	0.099	0.176	0.209

These proportions were applied back to the national STATS19 baseline numbers to determine the number of casualties (killed and seriously injured) and the percentages of frontal impact car occupant casualties and all car occupant casualties included in the target populations for Options 2 and 3 (see Table 23).

Table 23: Target population for GB (frontal impacts).

Impact type	Car occupant casualties		Target population			
	Killed	Seriously injured	Killed		Seriously injured	
			Option 2	Option 3	Option 2	Option 3
Car-to-car front	167	1684	59	88	734	840
Car-to-car side / rear	19	854	0	0	212	236
Car-to-HGV / PSV	52	263	0	2	12	12
Car-to-object	179	1801	26	26	540	672
Car-to-other / unknown	52	640	0	0	63	94
Car / multiple (3+ vehicles)	109	1010	8	11	177	211
Total	**579**	**6253**	**93**	**127**	**1739**	**2065**
Percentage of frontal impact car occupant casualties			**16%**	**22%**	**28%**	**33%**
Percentage of all car occupant casualties			**9%**	**12%**	**18%**	**21%**

4.2.4 Estimate of Benefit

Further detailed case analysis was undertaken to determine the benefit for occupants included in the target populations for Options 2 and 3. The benefit was calculated using an ‘injury reduction model’, which considered a casualty’s individual injuries.

Injury Reduction Model

Assumptions made in previous studies (VC-COMPAT [Cuerden 2006] and APROSYS [Edwards 2008]) were used to develop the model as follows:

- Improved compatibility will prevent compartment intrusion and improve the deceleration pulse in frontal impacts below test severity [Cuerden 2006]
  - Injury reduction models:
    - Pessimistic (lower): eliminate injuries caused by contact with an intruding front interior structure if ETS < 56 km/h.
    - Optimistic (upper): eliminate injuries caused by contact with the front interior (with or without intrusion) if ETS <56 km/h.
- Introduction of full width test will encourage improved restraint systems which will reduce restraint-related injury in frontal impacts [Edwards 2008]
  - Injury reduction models:
    - Model 1 (upper): reduce thorax and abdomen restraint-induced injuries to AIS 1 or by 2 AIS levels e.g. AIS 2 reduced to AIS 1; AIS 4 reduced to AIS 2.
    - Model 2: as Model 1 with ETS ≤ 56 km/h.
    - Model 3: as Model 2 with <5 cm intrusion on occupant’s side of the vehicle.
    - Model 4: as Model 3 but assuming no benefit for occupants > 65 years of age.

The injury reduction model used to estimate the benefit of Options 2 and 3 is outlined below.

The following assumptions were made for the full width test:

- The full width test will improve structural alignment and hence prevent or reduce compartment intrusion and improve the deceleration pulse where structural alignment is an issue.
- The full width test will encourage fitment of improved restraint systems and hence reduce restraint-related thorax, abdomen, clavicle and leg/pelvic injuries. There will be no reduction of upper extremity (arm) injuries.

The injury reduction model for the full width test is described below:

- Structural alignment improvement: for casualties in the target population where a structural alignment issue (i.e. over-/under-ride caused by a difference in vehicle structural heights) is identified:
  - Pessimistic (lower): reduce casualty injuries associated with contact with intrusion by up to 3 AIS levels (but not less than AIS1).
  - Optimistic (upper): reduce casualty injuries associated with contact with intrusion by up to 3 AIS levels (but not less than AIS1) and reduce injuries caused by the deceleration and restraint system (thorax, abdomen, clavicle and leg/pelvic injuries) by up to 1 AIS level (but not less than AIS1).
- Restraint system improvement: for casualties in the target population where a deceleration pulse has been identified specifically, reduce restraint-related injuries (thorax, abdomen, clavicle and leg/pelvic) by:
  - Pessimistic: 1 AIS level (but not less than AIS1).
  - Optimistic: 2 AIS levels (but not less than AIS1).

The following assumptions were made for the PDB test:

- The PDB test will improve structural interaction and hence prevent or reduce compartment intrusion and improve the deceleration pulse where this is an issue.
- The PDB test will improve frontal force matching and hence prevent or reduce compartment intrusion where this is an issue.

The injury reduction model for the PDB test is described below:

- Structural interaction improvement: for casualties in the target population where a structural interaction issue (i.e. over-/under-ride, fork effect or low overlap) is identified:
  - Pessimistic (lower): reduce casualty injuries associated with contact with intrusion by 3 AIS levels (but not less than AIS1).
  - Optimistic (upper): reduce casualty injuries associated with contact with intrusion by 3 AIS levels (but not less than AIS1) and reduce injuries caused by the deceleration and restraint system (thorax, abdomen, clavicle and leg/pelvic injuries) by up to 1 AIS level (but not less than AIS1).

- Frontal force matching / compartment strength improvement: for casualties in the target population where a frontal force issue is identified:
  - Pessimistic (lower): reduce casualty injuries associated with contact with intrusion by 3 AIS levels (but not less than AIS1).
  - Optimistic (upper): reduce casualty injuries associated with contact with intrusion by 3 AIS levels (but not less than AIS1) and reduce injuries caused by the deceleration and restraint system (thorax, abdomen, clavicle and leg/pelvic injuries) by up to 1 AIS level (but not less than AIS1).

Options investigated

A number of options were investigated within Options 2 and 3. These were:

- Full width test (**Option 2**)
  - Full width – structural alignment (FW_SA)
  - Full width – deceleration/restraint system (FW_D)
  - Full width – above together (FW_All)
- PDB test – structural interaction fork effect only
  - PDB – structural interaction fork effect (PDB_FE_SI)
  - PDB – frontal force matching (PDB_FE_FF)
  - PDB – above together (PDB_FE_All)
- PDB test – structural interaction over-/under-ride, fork effect or low overlap
  - PDB – structural interaction (PDB_All_SI)
  - PDB – frontal force matching (PDB_All_FF)
  - PDB – above together (PDB_All_All)
- Full width and PDB (**Option 3**)
  - Full width and PDB – structural interaction over-/under-ride, fork effect or low overlap (FW_PDB_All) (Option 3a).
  - Full width and PDB – structural interaction fork effect only (FW_PDB_FE) (Option 3b).

The pessimistic (lower) and optimistic (upper) assumptions shown above for the full width and PDB tests were applied to identify an estimated MAIS for each casualty included in the target population for each of the above 11 options. This was achieved through detailed case analysis involving examination of the occupant's injuries and the injury causation. Each casualty was assessed on an individual basis to allow for the identification of controlling injuries i.e. those for which no benefit is predicted for any of the options (e.g. extremity (arm) injuries where no contact with intrusion has occurred on the occupant side) and the identification of limiting injuries where injuries of the same AIS and different causes occurred (where this AIS was also the MAIS). Detailed case analysis examples are included in Annex A.

Car front to car front

MAIS	No. of casualties Original	FW_Upper	FW_Lower
1	0	25	20
2	47	30	34
3	19	16	16
4	5	2	3
5	5	3	3
6	1	1	1
Total	**77**	**77**	**77**

Car front to HGV/PSV

MAIS	No. of casualties Original	FW_Upper	FW_Lower
1	0	1	1
2	26	25	25
3	23	23	23
4	4	4	4
5	5	5	5
6	9	9	9
Total	**67**	**67**	**67**

Car front to car side/rear

MAIS	No. of casualties Original	FW_Upper	FW_Lower
1	0	10	9
2	33	27	25
3	17	16	19
4	7	4	4
5	0	0	0
6	0	0	0
Total	**57**	**57**	**57**

Car front to object

MAIS	No. of casualties Original	FW_Upper	FW_Lower
1	0	34	25
2	48	25	32
3	21	12	14
4	8	6	6
5	3	3	3
6	0	0	0
Total	**80**	**80**	**80**

Car front to other

MAIS	No. of casualties Original	FW_Upper	FW_Lower
1	0	4	2
2	14	12	14
3	15	13	13
4	4	4	4
5	0	0	0
6	0	0	0
Total	**33**	**33**	**33**

Figure 4.10: Change in MAIS calculated for casualties in the target population for Option 2 'Full Width test' by impact partner.

Car front to car front

MAIS	No. of casualties Original	FW_PDB_Upper	FW_PDB_Lower
1	0	35	26
2	47	29	35
3	19	9	11
4	5	1	2
5	5	2	2
6	1	1	1
Total	**77**	**77**	**77**

Car front to HGV/PSV

MAIS	No. of casualties Original	FW_PDB_Upper	FW_PDB_Lower
1	0	2	2
2	26	25	25
3	23	23	23
4	4	4	4
5	5	4	4
6	9	9	9
Total	**67**	**67**	**67**

Car front to car side/rear

MAIS	No. of casualties Original	FW_PDB_Upper	FW_PDB_Lower
1	0	13	11
2	33	27	26
3	17	13	16
4	7	4	4
5	0	0	0
6	0	0	0
Total	**57**	**57**	**57**

Car front to object

MAIS	No. of casualties Original	FW_PDB_Upper	FW_PDB_Lower
1	0	44	34
2	48	21	29
3	21	8	10
4	8	5	5
5	3	2	2
6	0	0	0
Total	**80**	**80**	**80**

Car front to other

MAIS	No. of casualties Original	FW_PDB_Upper	FW_PDB_Lower
1	0	5	3
2	14	12	14
3	15	12	12
4	4	4	4
5	0	0	0
6	0	0	0
Total	**33**	**33**	**33**

Figure 4.11: Change in MAIS calculated for casualties in the target population for Option 3a (full width and PDB) by impact partner.

Car front to car front

MAIS	No. of casualties Original	FW_PDB(FE)_Upper	FW_PDB(FE)_Lower
1	0	27	20
2	47	30	36
3	19	14	14
4	5	2	3
5	5	3	3
6	1	1	1
Total	**77**	**77**	**77**

Car front to HGV/PSV

MAIS	No. of casualties Original	FW_PDB(FE)_Upper	FW_PDB(FE)_Lower
1	0	2	2
2	26	24	24
3	23	23	23
4	4	4	4
5	5	5	5
6	9	9	9
Total	**67**	**67**	**67**

Car front to car side/rear

MAIS	No. of casualties Original	FW_PDB(FE)_Upper	FW_PDB(FE)_Lower
1	0	11	9
2	33	27	26
3	17	15	18
4	7	4	4
5	0	0	0
6	0	0	0
Total	**57**	**57**	**57**

Car front to object

MAIS	No. of casualties Original	FW_PDB(FE)_Upper	FW_PDB(FE)_Lower
1	0	42	32
2	48	22	30
3	21	9	11
4	8	5	5
5	3	2	2
6	0	0	0
Total	**80**	**80**	**80**

Car front to other

MAIS	No. of casualties Original	FW_PDB(FE)_Upper	FW_PDB(FE)_Lower
1	0	5	3
2	14	12	14
3	15	12	12
4	4	4	4
5	0	0	0
6	0	0	0
Total	**33**	**33**	**33**

Figure 4.12: Change in MAIS calculated for casualties in the target population for Option 3b (full width and PDB fork effect) by impact partner.

<u>Conversion of Change in MAIS to the Police Severity Scale</u>

To convert the benefit expressed in terms of change in MAIS to a benefit expressed in terms of the police injury severity scale (*i.e.* fatal, serious and slight), conversion factors were developed by comparing the proportions of MAIS 1 to 6 injured casualties to the proportions of fatal, serious and slight casualties. This was done for casualties in the baseline datasets for each impact partner type. The proportion of MAIS 1 to 6 injured casualties is compared to the proportion of fatal and seriously injured casualties for car front to car front impacts is illustrated in Table 24 as an example. (MAIS1 injuries were assumed to be ‘slight’ on the police severity scale for all impact types). The resulting conversion factors were applied to the new MAIS distributions (taking into account the estimated benefit for each occupant) to estimate the benefit in terms of the police injury severity scale (fatal, serious and slightly injured).

Table 24: Conversion of MAIS to police injury severity scale (car front to car front impacts).

Original MAIS	Number of casualties			Conversion factors		
	Fatal	Serious	Total	Fatal	Serious	Slight
1	0	0	0	0.000	0.000	1.000
2	0	47	47	0.000	1.000	0.000
3	4	15	19	0.211	0.789	0.000
4	4	1	5	0.800	0.200	0.000
5	4	1	5	0.800	0.200	0.000
6	1	0	1	1.000	0.000	0.000

Injury reduction factors were calculated for each option by comparing the numbers of fatally injured, seriously injured and slightly injured casualties in the original CCIS datasets with the numbers of fatally injured, seriously injured and slightly injured casualties in the target population following application of the injury reduction model to reduce injury in terms of MAIS. This process was followed for each of the 11 options (with pessimistic (lower) and optimistic (upper) assumptions). Predicted injury reduction factors for each impact partner type are shown in Table 25.

Table 25: Predicted injury reduction factors for each option by impact type.

Option	Reduction factor									
	Car front to car front		Car front to car side / rear		Car front to HGV / PSV		Car front to object		Car front to other	
	Fatal	Serious	Fatal	Serious	Fatal	Serious	Fatal	Serious	Fatal	Serious
FW_SA_Upp	0.938	0.966	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
FW_SA_Low	0.938	0.981	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
FW_D_Upp	0.705	0.700	0.571	0.829	1.000	0.980	0.806	0.546	0.947	0.867
FW_D_Low	0.767	0.766	0.571	0.847	1.000	0.980	0.806	0.673	0.947	0.938
FW_All_Upp	0.644	0.682	0.571	0.829	1.000	0.980	0.806	0.546	0.947	0.867
FW_All_Low	0.705	0.747	0.571	0.847	1.000	0.980	0.806	0.673	0.947	0.938
PDB_FE_SI_Upp	0.968	0.944	1.000	0.982	1.000	0.980	0.829	0.810	0.973	0.933
PDB_FE_SI_Low	0.984	0.988	1.000	1.000	1.000	1.000	0.926	0.911	0.973	0.969
PDB_FE_FF_Upp	0.968	0.975	1.000	1.000	1.000	1.000	0.903	0.998	1.000	1.000
PDB_FE_FF_Low	0.984	1.003	1.000	1.000	1.000	1.000	0.903	1.012	1.000	1.000
PDB_FE_All_Upp	0.919	0.923	1.000	0.982	1.000	0.980	0.731	0.809	0.973	0.933
PDB_FE_All_Low	0.968	0.991	1.000	1.000	1.000	1.000	0.829	0.923	0.973	0.969
PDB_All_SI_Upp	0.718	0.854	1.000	0.893	0.944	0.980	0.731	0.696	0.973	0.933
PDB_All_SI_Low	0.845	0.907	1.000	0.964	0.944	1.020	0.926	0.883	0.973	0.969
PDB_All_FF_Upp	0.796	0.963	1.000	0.982	1.000	1.000	0.903	0.998	1.000	1.000
PDB_All_FF_Low	0.906	0.988	1.000	1.000	1.000	1.000	0.903	1.012	1.000	1.000
PDB_All_All_Upp	0.608	0.798	1.000	0.893	0.944	0.980	0.634	0.694	0.973	0.933
PDB_All_All_Low	0.751	0.894	1.000	0.964	0.944	1.020	0.829	0.895	0.973	0.969
FW_PDB_FE_Upp	0.611	0.657	0.571	0.811	1.000	0.959	0.634	0.455	0.920	0.836
FW_PDB_FE_Low	0.673	0.754	0.571	0.847	1.000	0.959	0.634	0.596	0.920	0.907
FW_PDB_All_Upp	0.407	0.574	0.571	0.776	0.944	0.980	0.634	0.427	0.920	0.836
FW_PDB_All_Low	0.501	0.695	0.571	0.811	0.944	0.980	0.634	0.567	0.920	0.907

CCIS Proportions

Benefit proportions of fatally injured and seriously injured casualties estimated for the CCIS dataset are illustrated for the target population and Option 2 (full width), Option 3a (full width and PDB full) and Option 3b (full width and PDB fork effect) for all impact types in Table 26 (fatally injured casualties) and Table 27 (seriously injured casualties), including pessimistic (lower) and optimistic (upper) assumptions.

Table 26: Target population and benefit proportions estimated for CCIS dataset for Options 2, 3a and 3b (fatally injured casualties).

Impact type	CCIS benefit proportions							
	Target population		Option 2		Option 3a		Option 3b	
	Option 2	Option 3	Upper	Lower	Upper	Lower	Upper	Lower
Car-to-car front	0.353	*0.529*	0.272	0.225	0.453	0.381	0.297	0.250
Car-to-car side / rear	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Car-to-HGV / PSV	0.000	0.046	0.000	0.000	0.046	0.046	0.000	0.000
Car-to-object	0.144	0.144	0.063	0.063	0.119	0.119	0.119	0.119
Car-to-other / unknown	0.000	0.000	0.033	0.033	0.050	0.050	0.050	0.050
Car / multiple (3+ vehicles)	0.072	0.099	0.011	0.008	0.032	0.023	0.015	0.011

Table 27: CCIS proportions (target population and Options 2, 3a and 3b) (seriously injured casualties).

Impact type	CCIS benefit proportions							
	Target population		Option 2		Option 3a		Option 3b	
	Option 2	Option 3	Upper	Lower	Upper	Lower	Upper	Lower
Car-to-car front	0.436	0.499	0.254	0.202	0.340	0.243	0.274	0.196
Car-to-car side / rear	0.248	0.276	0.132	0.118	0.173	0.146	0.146	0.118
Car–to-HGV / PSV	0.046	0.046	0.015	0.015	0.015	0.015	0.030	0.030
Car-to-object	0.300	0.373	0.236	0.170	0.298	0.225	0.283	0.210
Car-to-other / unknown	0.098	0.147	0.092	0.043	0.113	0.064	0.113	0.064
Car / multiple (3+ vehicles)	0.176	0.209	0.024	0.014	0.041	0.022	0.031	0.017

Estimated Benefit

The CCIS dataset benefit proportions above were used to scale the national data to estimate the benefit for GB. The estimated benefit (in terms of casualties saved) for each impact type is shown for Option 2 (full width), Option 3a (full width and PDB full) and Option 3b (full width and PDB fork effect) in Table 28 (fatally injured casualties) and Table 29 (seriously injured casualties), including pessimistic (lower) and optimistic (upper) assumptions.

Table 28: Benefit for GB (in terms of casualties saved) for Options 2, 3a and 3b for fatally injured casualties.

Impact type	Car occupant casualties	Target population		Benefit (casualties saved)					
				Option 2		Option 3a		Option 3b	
		Option 2	Option 3	Upper	Lower	Upper	Lower	Upper	Lower
Car-to-car front	167	59	88	46	38	76	64	50	42
Car-to-car side / rear	19	0	0	0	0	0	0	0	0
Car-to-HGV / PSV	52	0	2	0	0	2	2	0	0
Car-to-object	179	26	26	11	11	21	21	21	21
Car-to-other / unknown	52	0	0	2	2	3	3	3	3
Car / multiple (3+ vehicles)	109	8	11	1	1	3	3	2	1
Total	**579**	**93**	**127**	**60**	**52**	**105**	**93**	**75**	**67**
Percentage of all car occupant casualties		**9%**	**12%**	**6%**	**5%**	**10%**	**9%**	**7%**	**6%**

Table 29: Benefit for GB (in terms of casualties saved) for Options 2, 3a and 3b for seriously injured casualties.

Impact type	**Car occupant casualties**	**Target population**		**Benefit (casualties saved)**					
				Option 2		**Option 3a**		**Option 3b**	
		Option 2	**Option 3**	**Upper**	**Lower**	**Upper**	**Lower**	**Upper**	**Lower**
Car-to-car front	1684	734	840	428	340	573	410	461	331
Car-to-car side / rear	854	212	236	3	2	3	3	3	2
Car-to-HGV / PSV	263	12	12	4	4	4	4	8	8
Car-to-object	1801	540	672	425	307	537	405	511	379
Car-to-other / unknown	640	63	94	59	27	72	41	72	41
Car / multiple (3+ vehicles)	1010	178	211	24	14	41	22	32	17
Total	**6253**	**1739**	**2065**	**943**	**694**	**1231**	**885**	**1086**	**777**
Percentage of all car occupant casualties		**18%**	**21%**	**10%**	**7%**	**13%**	**9%**	**11%**	**8%**

Table 30: Breakdown of benefit for Option 2 'full width test' for fatally injured casualties.

Impact type	Car occupant casualties	Target population		Benefit (injury reduction)					
				Option 2		Option 2 - SA		Option 2 - D	
		Option 2	Option 3	Upper	Lower	Upper	Lower	Upper	Lower
Car to car front	167	59	88	46	38	8	8	38	30
Car to car side / rear	19	0	0	0	0	0	0	0	0
Car to HGV / PSV	52	0	2	0	0	0	0	0	0
Car to object	179	26	26	11	11	0	0	11	11
Car to other / unknown	52	0	0	2	2	0	0	2	2
Car / multiple (3+ vehicles)	109	8	11	1	1	0	0	1	1
Total	**579**	**93**	**127**	**60**	**52**	**8**	**8**	**52**	**43**
Percentage of all car occupant casualties		**8.9%**	**12.1%**	**6%**	**5%**	**0.8%**	**0.8%**	**5%**	**4%**

A breakdown of the benefit resulting from Option 2 (full width) structural alignment improvement and restraint system improvement is shown in

Table 30 (fatally injured casualties) and Table 31 (seriously injured casualties). These results show that the majority of the benefit predicted for Option 2 is from the restraint system improvement (with a resulting reduction in the severity of deceleration-related injuries).

Table 31: Breakdown of benefit for Option 2 'full width test' for seriously injured casualties.

Impact type	Car occupant casualties	Target population		Benefit (injury reduction)					
				Option 2		Option 2 - SA		Option 2 - D	
		Option 2	Option 3	Upper	Lower	Upper	Lower	Upper	Lower
Car to car front	1684	734	840	428	340	46	25	403	314
Car to car side / rear	854	212	236	3	2	0	0	3	2
Car to HGV / PSV	263	12	12	4	4	0	0	4	4
Car to object	1801	540	672	425	307	0	0	425	307
Car to other / unknown	640	63	94	59	27	0	0	59	27
Car / multiple (3+ vehicles)	1010	178	211	24	14	0	0	23	13
Total	**6252**	**1739**	**2065**	**943**	**694**	**46**	**25**	**916**	**667**
Percentage of all car occupant casualties		**17.7%**	**21%**	**10%**	**7%**	**0.5%**	**0.3%**	**9%**	**7%**

4.3 Target Population for Side Impact

The above analysis focused on car occupants involved in frontal impacts. It was assumed that if lower load paths are fitted to car fronts to improve their compatibility in frontal impacts, this will also help compatibility in side impacts and hence could reduce the number of casualties in cars impacted on the side by the fronts of other cars. This is because a lower load path should enable better interaction with the sills of cars impacted on the side.

The analysis started with the baseline i.e. Option 1 'No change' (calculated as described above using regression analysis and STATS19 data) with Killed or Seriously Injured (KSI) car occupant casualties in side impacts in a regulatory compliant and/or Euro NCAP-influenced vehicle fleet Table 32 summarises the number of killed and seriously injured car occupant casualties in side impacts by impact partner type.

Table 32: Car occupant casualties in car side impacts in a regulatory compliant / Euro NCAP influenced vehicle fleet.

Impact type	Car occupant injury severity	
	Killed	**Seriously injured**
Car side hit by car front	80	656
Car side hit by car side / rear	14	309
Car side hit by HGV / PSV	29	120
Car side hit by object	143	732
Car side hit by other / unknown	40	282
Car side hit by multiple (3+ vehicles)	40	226
Total	**346**	**2325**

An equivalent baseline CCIS dataset (i.e. the comparison point with baseline national STATS19 data) for occupants in side impacts was derived by applying the following selection criteria:

- Accident occurred between 2000 and 2010 (inclusive).
- The casualty was killed or seriously injured (MAIS 2+)
- The casualty was a car occupant.
- A significant side impact occurred.
- The car side was hit by the car front.
- The nature of the injury was known.
- The occupant was in a regulatory compliant car.

A further set of selection criteria was applied to each dataset to identify those casualties who may experience a benefit if the vehicle's front end was modified to improve its compatibility in side impacts. The following criteria were applied:

- No rollover occurred before the first impact.
- Damage to the passenger compartment occurred.
- The direction of force was between 1 and 5 or between 7 and 11.

The selection process to determine the target population in the detailed CCIS dataset is illustrated in Figure 4.13.

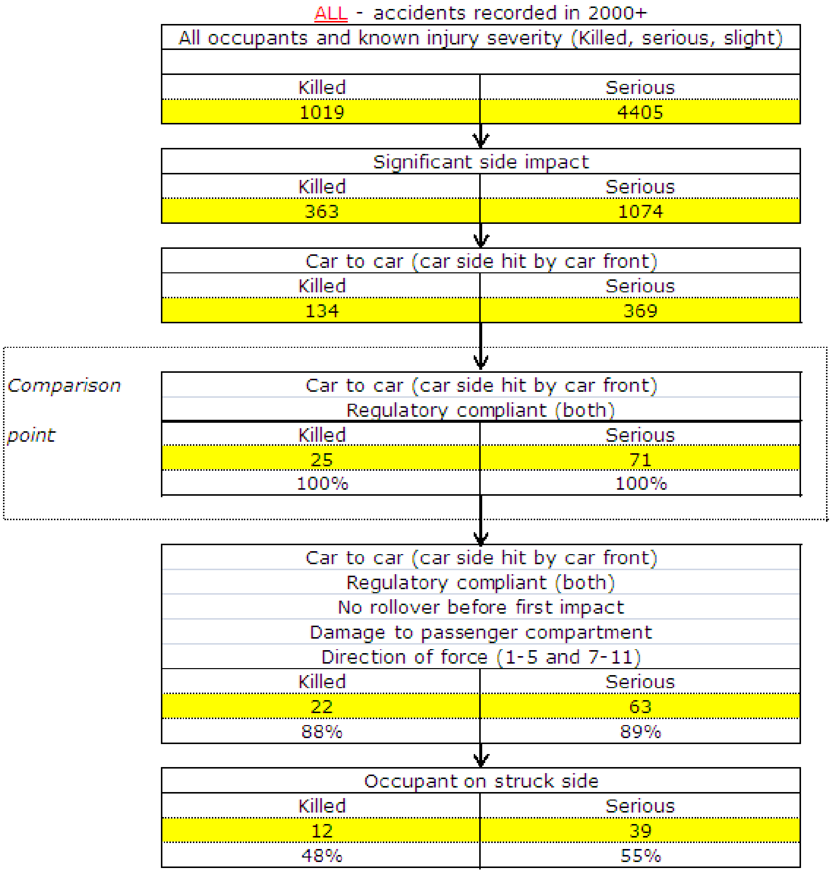


Figure 4.13: Formation of equivalent baseline CCIS dataset for side impacts.

<u>CCIS Proportions and Scaling to the National Dataset</u>

Table 29 shows the proportions of casualties in the CCIS equivalent baseline datasets included in the target population for side impacts. (Note: the proportion of casualties in the target population for the impact type ‘car / multiple (3+ vehicles)’ was calculated by estimating the number of casualties in multiple vehicle accidents in which the vehicle has a significant side impact and applying a weighted average of the proportions for other impact types to these casualties). The proportions were calculated for occupants on the struck side of the vehicle only and for occupants on either the struck or non-struck side.

Table 30: CCIS target population proportions (side impacts).

Impact type	CCIS target population proportions			
	Killed		Seriously injured	
	Struck and non-struck side	Struck side only	Struck and non-struck side	Struck side only
Car side hit by car front	0.88	0.48	0.89	0.55
Car side hit by car side / rear	0	0	0	0
Car side hit by HGV / PSV	0	0	0	0
Car side hit by object	0	0	0	0
Car side hit by other / unknown	0	0	0	0
Car side hit by multiple (3+ vehicles)	0.079	0.043	0.126	0.078

These proportions were applied to the national STATS19 baseline numbers to determine the number of casualties (killed and seriously injured) and the percentages of side impact car occupant casualties and all car occupant casualties in the target population (see Table 31).

Table 31: Target population for GB for side impact.

Impact type	Car occupant injury severity		Target population			
	Killed	Seriously injured	Killed		Seriously injured	
			Struck and non-struck side	Struck side only	Struck and non-struck side	Struck side only
Car side hit by car front	80	656	71	39	584	361
Car side hit by car side / rear	14	309	0	0	0	0
Car side hit by HGV / PSV	29	120	0	0	0	0
Car side hit by object	143	732	0	0	0	0
Car side hit by other / unknown	40	282	0	0	0	0
Car side hit by multiple (3+ vehicles)	40	226	3	2	28	18
Total	**346**	**2325**	**74**	**40**	**613**	**379**
Percentage of side impact car occupant casualties			**21%**	**12%**	**26%**	**16%**
Percentage of all car occupant casualties			**7%**	**4%**	**6%**	**4%**

The overall benefit of improved compatibility for casualties in the target population (side impacts) is summarised in Table 32.

Table 32: Target population for side impact.

Option	% (Number) of car occupant casualties			
	Killed		Seriously injured	
	Struck and non-struck side	Struck-side only	Struck and non-struck side	Struck-side only
Target population for side impact casualties	7.1%	3.8%	6.2%	3.9%
	(74)	(40)	(613)	(379)

4.4 Summary of Conclusions

4.4.1 Benefit of Option 1 'No change'

The benefits for Option 1 'No change' for casualties in frontal and side impacts were:

- Frontal impact
  - Regression analysis estimates a benefit of 2.0% (21) of killed and 1.7% (164) of seriously injured car occupant casualties
  - However, for the car-to-car frontal impact subset both proportional and regression analyses show that the number of fatal casualties increases with newer cars. This may indicate that the increased self-protection of cars is being offset by their increased aggression
- Side impact
  - Regression analysis estimates a benefit of 3.1% (32) of killed and 1.7% (171) of seriously injured car occupant casualties
  - For the car-to-car side impact subset both the proportional and regression analyses show that the number of fatal casualties decreases with newer (regulatory compliant / Euro NCAP influenced) cars.

4.4.2 Target Populations and Benefits for Option 2 'Full Width Test' and Option 3 'Full Width and PDB Tests'

The target populations and benefits predicted for Option 2 'Full Width test', Option 3a ' Full Width and PDB Tests' and Option 3b 'Full Width and PDB test – fork effect only' is summarised in Table 33 (Note: this does not include the benefit of Option 1 'no change').

Table 33: Summary of target population and benefits for GB for implementation of Options 2, 3a and 3b.

Option		% (No.) of car occupant casualties			
		Killed		Seriously injured	
Target population	Option 2 'Full width test'	8.9% (93)		17.7% (1739)	
	Option 3 'Full width & PDB tests'	12.1% (127)		21.0% (2065)	
Benefit	Option 2 'Full width test'	Upper	Lower	Upper	Lower
		6% (60)	5% (52)	10% (943)	7% (694)
	Option 3a 'Full width & PDB test full'	Upper	Lower	Upper	Lower
		10% (105)	9% (93)	13% (1231)	9% (885)
	Option 3b 'Full width & PDB test fork effect only'	Upper	Lower	Upper	Lower
		7% (75)	6% (67)	11% (1086)	8% (777)

The benefit for Option 2 'Full Width test' was examined further and the proportion of it related to improvements in structural alignment and improvements to the restraint system were estimated as shown in Table 34.

It should be noted that the target populations and benefits estimated in this section do not include the benefit of Option 1 'No change'. Also, the benefit related to structural alignment is likely to be under estimated because misaligned vehicles were difficult to identify in the accident data.

Table 34: Breakdown of the benefit for Option 2 'Full Width test'.

Option		% (No.) of car occupant casualties			
		Killed		Seriously injured	
Target population	Option 2 'Full width test'	8.9% (93)		17.7% (1739)	
Benefit	Option 2 'Full width test'	Upper	Lower	Upper	Lower
		6% (60)	5% (52)	10% (943)	7% (694)
	Option 2 'Full width test - structural alignment'	Upper	Lower	Upper	Lower
		0.8% (8)	0.8% (8)	0.5% (46)	0.3% (25)
	Option 2 'Full width test - deceleration'	Upper	Lower	Upper	Lower
		5% (52)	4% (43)	9% (916)	7% (667)

4.4.3 Target Population for Side Impact

The target population was estimated for casualties in car side impacts in which the car was struck by another car which had improved compatibility. Two estimates were made, the first (optimistic/upper) assumed that occupants seated on the struck and non-struck side may experience benefit, the second (pessimistic/lower) that only occupants seated on the struck may experience benefit (Table 35).

Table 35: Target population for side impacts.

Option	**% (Number) of car occupant casualties**			
	Killed		**Seriously injured**	
	Struck and non-struck side	**Struck-side only**	**Struck and non-struck side**	**Struck-side only**
Target population for side impact casualties	7.1%	3.8%	6.2%	3.9%
	(74)	(40)	(613)	(379)

5 GERMAN ANALYSIS

As for GB, the German analysis was performed in two parts; the first part estimated the benefit for Option 1 (No change) and the second part the benefits and break-even costs for Option 2 (FW test) and Option 3 (FW and PDB tests).

5.1 Benefit of Option 1 'No change'

5.1.1 Methodology

German national accident data with personal injury from years 2005 to 2007 were used for this analysis, which were presented in Geneva in 2009 [Pastor 2009/1, Pastor 2009/2]. The high importance of two-car-accidents can be illustrated as follows. Two-car-accidents deliver more than half of the accidents with personal injury to a passenger car driver and about a quarter of all passenger car driver fatalities. Among those accidents, front-to-front accidents are of particular high importance. Front-to-front two-car-accidents make up about 12 % of all two-car-accidents, but produce more than 50 % of all-two-car accidents driver fatalities (***Figure 5.3***). For this reason – and because other categories of frontal car impacts were difficult to identify in police accident data – only front-to-front two-car-accidents were considered in this analysis.

For this investigation a matched pairs approach was chosen. In contrast to other methods - e.g. analysing indicators like Severity Rate, which is defined as the ratio of the count of driver fatality plus seriously injured drivers and the count of all personally injured drivers – this kind of statistical approach does not neglect the possible correlation of two road users that are involved in the same accident (no independent observations).

The method used was the "Bradley Terry Model". This model deals with the area of paired comparisons, where ranking takes place between members drawn from a group two at a time. Whereas the method has often been used to establish rankings and predictions for sports competitions, the method was now used to establish crashworthiness rankings for passenger cars.

Whereas the winner in a sports duel is easy to see, the winner in a car-to-car crash was defined as the car which received less injury to its driver. The model can be formulated as follows:

$p_{ij} = \alpha_i / (\alpha_i + \alpha_j)$; $Odds_{ij} = \alpha_i / \alpha_j$; (2), (3)

with: P_{ij} : *Winning Probability car i against car j;*

α_i : *Crashworthiness of car i*

The model can alternatively be formulated as a log linear model where independent (explanatory) parameters can be introduced.

The parameters selected were primarily age and gender of the passenger car driver, frontal impact Euro NCAP rating and the mass of the car. Secondary, parameters as the wheelbase/total length, total width and height, the specific power and the manufacturer were considered. Based on these factors the crashworthiness (CW) was calculated.

Finally the injury risk for a car occupant was estimated. The injury risk for the driver of one particular car was considered to be a function of

- (1) the accident severity in general,
- (2) the partner protection of the other car and
- (3) the self protection/crashworthiness of the reference or case car

The general accident severity (1) will probably depend on accident related parameters such as, e.g. "location of accident". Rural accidents are for instance in general more severe than urban accidents because of higher driving speeds.

Any given general accident severity can be made more severe by an aggressive collision opponent, or vice versa can be made less severe by some smart collision opponent. This partner protection term (2) was easily constructed to be the difference in crashworthiness between the partners. A collision opponent with identical crashworthiness (basically a car with the same mass, the same NCAP rating) will not make the accident more or less severe.

Finally the given accident severity was taken into account (absorbed) in the cars' crashworthiness (3), as it was estimated by the Bradley Terry Model. The injury risk of car A was then calculated using a standard logistic regression approach.

Accident Severity, $\boldsymbol{S}$ *(given accident severity)*

Partner Protection, $\boldsymbol{D_{AB}}$ *(is distributed among partners)*

Self Protection, $\boldsymbol{CW_A}$ *(has to be absorbed)*

Figure 5.1: Input for the estimation of injury risk of a car-to-car accident.

The final statistical model, using the inputs shown in Figure 5.1, is able to fully explain the current injury severity distribution of passenger car drivers involved in car–to-car front to front collisions. It is now of particular interest to see how this injury severity distribution may be modified by different future scenarios.

One of the options being of interest is the "do nothing option". Here it is assumed that no changes to the current frontal impact regulation will be introduced. The car fleet will develop without applying additional constraints. It has been assumed that the newer cars will become heavier, simply because the older cars will leave the fleet and will be substituted by more modern cars, which have shown to have a greater mass (by a factor of around 1.3). In addition the frontal safety level of new cars, substituting the old ones, was considered to be 9-12 points in terms of NCAP rating.

5.1.2 Results

5.1.2.1 Overview of Car Occupant Casualties in Germany

Figure 5.2 shows road accident casualties by user type for Germany for the average of years 2005 - 2007. It can be seen that approximately half of the fatally injured people were car users, similar to GB. ***Figure 5.3*** shows the breakdown by impact type for car occupant fatalities for 2008. Single car accidents are the biggest group of fatalities with 42%, with nearly half of them being frontal collisions. Car-to-car accidents make the second biggest group of fatalities with 24%, with about half of them being car front-to-front accidents and half car-to-other impact types.

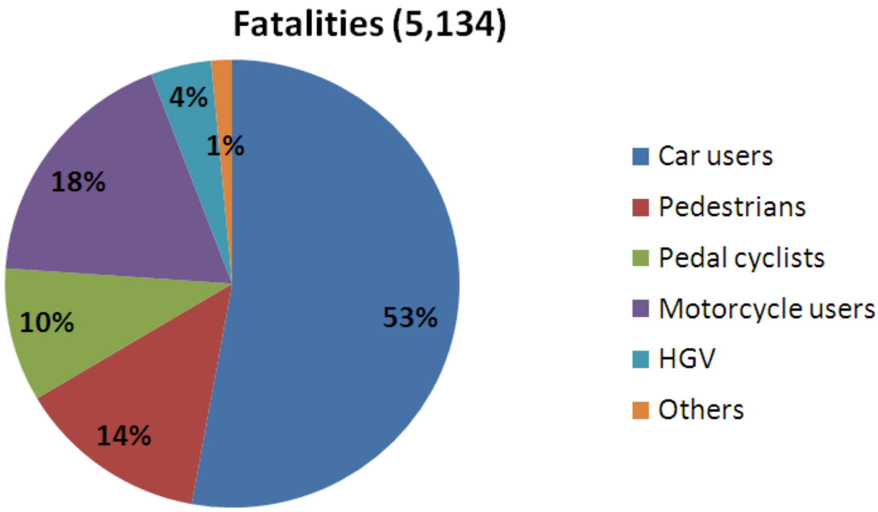
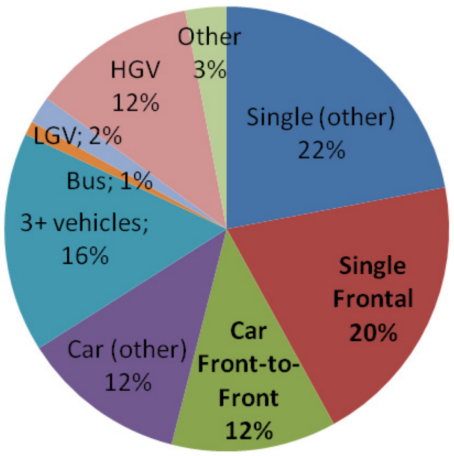


Figure 5.2: Road accident fatalities in Germany by user type average 2005-2007.



5.1.2.2 Figure 5.3: Car occupant fatalities in year 2008 (German National Accident Data).Matched pairs analysis

The statistical model as described in the methodology part was applied to 21,764 two car front-to-front accidents. The statistical model outlined, describing the injury severity risk for some driver is visually shown in Figure 5.4. The statistical significance and effects of "partner protection", "self protection" and "accident severity in general" as driving factors determining the injury severity risk is given in terms of Odds Ratio. Odds Ratios of 1 describe factors which do not influence the injury risk (roughly speaking the Odds Ratio is fifty/fifty, which is identical to 1). This is, for example, true for the effect of the self protection term in the model, where the Odds Ratio is nearly 1. The bars in different grey shadings attached to the calculated Odds Ratio shows the confidence interval of the estimate. In particular, if the bars cross the Odds Ratio line at 1, no significant effect can be seen.

It is somehow surprising that the self protection term did not show up to have a significant effect. It has to be mentioned that some "self protection" term is already integrated in the definition of the "partner protection" term. The "partner protection" term is highly relevant and significant. However, the right interpretation/reading of the minor "self protection" effect is, that – provided there is no dangerous collision opponent and the accident severity in general is similar – the injury risk for the driver does not depend heavily on the crashworthiness of the car they are in. This result is in line with conclusions from some frontal impact research work recently done by TRL for the European Commission [Richards 2010]. In the paper (Tables 11, 12 and 13) it is shown that the risk for getting fatally injured in a front to front car-to-car crash is primarily dependent on the model year of the collision opponent, but independent of the model year of the reference car.

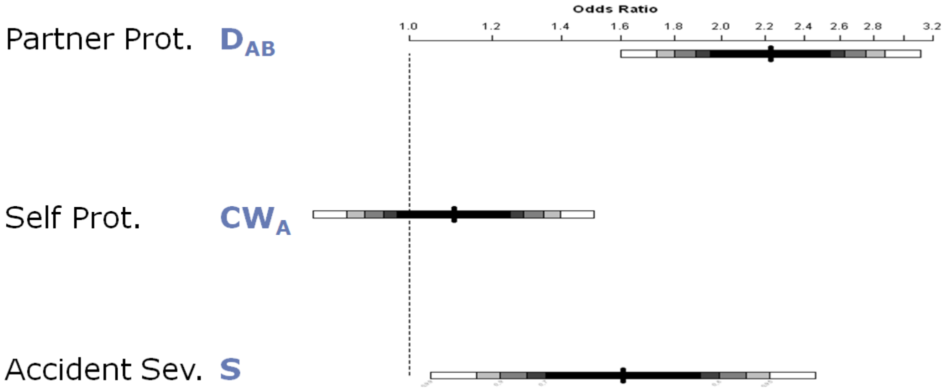


Figure 5.4: Importance of factors driving injury risk for car A.

5.1.3 Estimate of Benefit and Conclusions

The factors mentioned were used to calculate the benefit of changing to a regulatory compliant / Euro NCAP influenced fleet (defined as vehicles registered 2000+ with a Euro NCAP frontal score of 9-12) as shown in Table 36 and Table 37 for option 1 'no change'.

Table 36: Outcome of Option 1 'No change' based on 21,764 front-to-front two car accidents.

	Fatalities	Seriously injured	Slightly injured	Uninjured
Current situation	100.0 %	100.0 %	100.0 %	100.0 %
Option 1	98.2 %	100.1 %	100.0 %	100.4 %

Table 37: Benefit of Option 1 'No change' for car-to-car frontal impacts (Germany).

Benefit of Option 1, 'No change'	% of car occupant casualties	
	Killed	Seriously injured
Casualties	-1.8 %	0.1 %

It is interesting to note that a benefit is estimated for two-car frontal accidents for killed casualties in contrast to the GB analysis which predicts a disbenefit. However, the German analysis did consider some additional factors for the evolution of the car fleet (higher masses of new cars and some better self protection as a result of the general technical improvement). This could be a reason for such differing results.

5.2 Benefit of Option 2 'Add Full Width Test' and Option 3 'Add Full Width Test and Replace Current ODB Test with PDB Test'

5.2.1 Methodology

For this analysis, the GIDAS database was used because the detailed information necessary to perform the analysis was not available in the German national statistics.

The selection of the dataset and the identification of the target population were performed in a similar manner as for the CCIS dataset for the GB analysis apart from the necessity of a different data handling process. In detail, the data query from the accident data analysis (see

Deliverable 1.1) [Thompson 2013] to extract car frontal collisions was used as for the GB analysis. The following criteria were applied to derive the dataset:

- Accident occurred between 2000 and 2010 (inclusive).
- The casualty was killed or seriously injured.
- The casualty (driver and/or front passenger) was a car occupant and older than 12 years.
- A significant frontal impact occurred with the frontal force direction (11, 12 or 1 o'clock), main damage to the front and no rollover.
- The nature of the injury, the impact type and seatbelt use were all known.
- Cars with first registration of years 2000 to 2009.

A further set of selection criteria was applied to identify those casualties where a benefit may be achieved for the chosen options, such as the known usage of the belt. The focus of the analysis was then focused on fatalities and seriously injured people (MAIS 2+). The associated accidents were categorised on a casualty level by a case-by-case analysis to the defined compatibility issues or to the category 'no issue' (see section 4.2.3):

- Structural interaction (scope)
- Front End Force / Deformation
- Compartment integrity
- Restraint system
- No issue

The alignment to these categories was done mainly by investigating photos, described accident causation, the injury overview (single injuries were summarised per body region; for each body region (highest AIS) main injury causation is assigned), driver behaviour and expert judgment. In general, if the compartment integrity failed, then it was likely that a compatibility issue occurred. 'No issue' was assigned if e.g. the car was totally destroyed by extreme speeding and hence, these high severity damages could not be assigned to certain compatibility issues impacts or addressed by resolving them.

The benefit was estimated for each option separately for each casualty in the target population by the use of an injury-shifting-method. Major steps for the assignment of injured people to the target population with regard to their injuries were:

- Consideration of all injuries
- Determination of highest AIS level per body region and its causation
- Assignment of those injuries to compatibility issues / no issues.

However, for the benefit analysis a different injury reduction model was used compared to the CCIS analysis. Initially each person's most seriously injured body region (expressed by MAIS) was determined. Following this, it was determined if the MAIS injury(ies) were caused by, or related to, a compatibility issue. They were then considered for the injury reduction model as described below. Due to the low number of fatalities in the GIDAS dataset, the killed and seriously injured (KSI) casualties were treated as one group to ensure statistically meaningful results.

The following injury reduction model (injury severity shifting method) was applied to calculate the casualty injury reduction to estimate the benefit of Options 2 and 3:

- MAIS reduction for casualties in target population:
  - Killed:
    - Full-width: MAIS minus 1 -> considered seriously injured if MAIS 4 or less
    - PDB: MAIS minus 1 -> considered seriously injured if MAIS 4 or less
  - Seriously injured:
    - Full-width: MAIS minus 1, but minimum MAIS 1 -> considered slightly injured if MAIS less than 2
    - PDB: MAIS minus 1, but minimum MAIS 1 -> considered slightly injured if MAIS less than 2
  - Slightly injured (MAIS 1) stay slightly injured
- Optimistic estimate for upper limit: all killed and seriously injured in target population have their injuries reduced as above.
- Pessimistic estimate for lower limit: half of all killed and seriously injured in target population have their injuries reduced as above.

Finally, the national benefit was estimated as the change of the proportion of killed and seriously injured casualties scaled to the national level.

5.2.2 Estimate of Target Population

The analysis of GIDAS passenger car frontal collisions of the years 2000 to 2010 included all kinds of collision partners and impact configurations to other vehicles or objects (Frontal-frontal, Frontal-side, Frontal-rear, Frontal-object/others). The dataset contained:

- Number of cases: 2862
- Number of cars involved: 2950
- Number of people in those cars: 3650

Table 41 shows an overview of people involved in the final dataset, whereby a distinction was chosen into the collision partner groups CAR_CAR (car-to-car), CAR_HGV (car-to-heavy good vehicles), CAR_OBJ (car-to-objects) and CAR_OTH (car-to-others). It can be seen that most KSI injured people (56%) were involved in car-to-car crashes, but a higher proportion of killed cases occur in car-to-object (e.g. tree) and car-to-heavy good vehicles accidents.

Table 38: GIDAS dataset used (person level, seatbelt use known)

	KSI	Slightly injured	Uninjured	Unknown	Total	Killed
CAR_CAR	111 (56%)	623	958	35	1727	4
CAR_HGV	22 (11%)	69	21	8	120	3
CAR_OBJ	64 (32%)	162	305	22	553	6
CAR_OTH	2 (1%)	15	816	0	833	0
TOTAL	199 (100%)	869	2100	65	3233	13

The process was followed by a reduction of four potential cases due to missing information. Thus, the GIDAS data sample for the detailed case analysis was reduced to 195 killed or seriously injured car occupant casualties. Due to the low numbers of cases no further distinctions have been made in the following work in terms of collision partner groups. The result of this analysis to determine the target populations is shown in Figure 5.5. Casualties were identified in which there were compatibility problems and restraint performance issues in the accident as described in the methodology section above. The relationship of the problem to the test is shown by the green and orange boxes, e.g. there is a green box around deceleration because the full width test should help reduce deceleration restraint related injuries. Nearly half of all cases were assigned to the category 'No issues', while 41% were assigned to 'Deceleration' related injuries and 13% to 'Compatibility issues'.

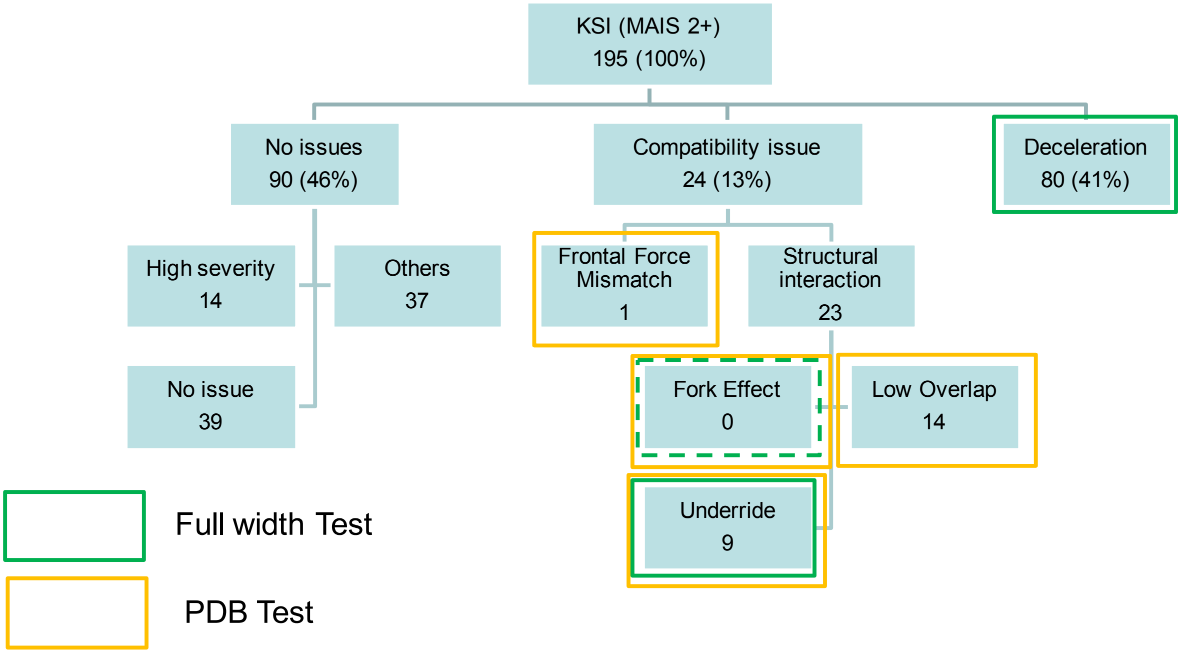


Figure 5.5: German (GIDAS) detailed data sample target population breakdown KSI (MAIS 2+).

These results were then scaled up to national level. An assumption taken to scale to national data level was that 42% of all killed and seriously injured people in cars occur in frontal collisions in Germany. The proportions for the target population for the options 2 and 3 can be seen in Table 42.

5.2.3 Estimate of Benefit

The target populations and benefits for Germany are shown below in a similar manner as for GB, see Table 33. Target populations and benefits shown do not include the benefit of Option 1 'No change'.

Table 39: Target populations and benefits for Options 2 and 3 (Germany).

Option		% (No.) of car occupant casualties Killed and seriously injured	
Target population	Option 2 'Full-width test'	16% (5085)	
	Option 3 'Full-width & PDB test'	19% (5942)	
Benefit	Option 2 'Full-width test'	**Upper** 12% (3771)	**Lower** 6% (1886)
	Option 3 'Full-width & PDB test'	**Upper** 14% (4343)	**Lower** 7% (2171)

The target population for Option 2 was calculated to be16% and for Option 3 to be 19% of car occupant casualties with at least serious injuries, respectively. The benefit varies, for Option 2 between 6% and 12% and for Option 3 slightly higher between 7% and 14%. The breakdown of the benefit of Option 2 shows that a major part of it would be addressed by an improved restraint system for car occupants, see Table 43.

Table 40: Breakdown of the benefit of Option 2 (Germany).

Option		% (No.) of car occupant casualties Killed and seriously injured	
Target population	Option 2 'Full-width test'	16% (5085)	
Benefit	Option 2 'Full-width test'	**Upper** 12% (3771)	**Lower** 6% (1886)
	Option 2 'Full-width test - structural alignment'	**Upper** 0.7% (229)	**Lower** 0.4% (114)
	Option 2 'Full-width test - deceleration'	**Upper** 11% (3543)	**Lower** 6% (1771)

5.3 Summary of Conclusions

- The benefit for option 1 'No change' was estimated to 1.8% less fatalities and 0.1% more seriously injured people by a matched pairs analysis of national data from 2005-2007. The benefits for option 2 'Add full width test to ODB test' and for option 2 'Add full-width test and replace ODB by PDB test' were estimated to be within the ranges of 6 - 12% of KSI (killed and seriously injured car occupants) and 7 - 14%, respectively.
- Compared to the GB analysis, the German analysis for Options 2 and 3 only states joint results for killed and seriously injured people, because a further distinction and hence scaling was not reasonable for the small number of fatalities within the selected GIDAS data set. Nevertheless, proportions for the target populations as well as for the benefits calculated are quite similar for GB and Germany.
- It should be noted that the case-by-case analysis of CCIS and GIDAS data in terms of identifying defined compatibility issues was mainly similar but there were some small differences due to subjective judgements (e.g. frontal tree collisions were mainly assigned to 'Fork effect' by TRL but to 'Deceleration' or 'No issue' by BASt).

6 EUROPEAN ANALYSIS

This work involved scaling the benefit proportions estimated for Great Britain (GB) and Germany (D) described above to give an indicative estimate of the benefits for Europe for each option. The approximate nature of this estimate should be remembered because it was assumed that the accident scene in GB and Germany is representative of that across the whole of Europe which is not accurate.

Fatal and seriously injured casualty data for all casualties and car occupant casualties were extracted from CARE [EC 2013.] for each country in the EU by year (Table 41). Points to note are:

- Fatal casualties were defined as those killed within 30 days of the collision. In a number of countries, the time period is much shorter, so an adjustment was made to account for this.
- 'Seriously injured' does not have a common definition across Europe; there may be differences in the classification of casualties between countries.
- 2008 data were the most recent data available for all countries in EU-15; as a result, these data was used. A number of countries have shown casualty reductions since 2008, so benefit figures calculated may be an overestimate.
- EU-27 excludes Bulgaria and Lithuania as data were not available from CARE for these countries.
- Data for Cyprus were only available for 2004, so these data were used.
- Seriously injured casualty data were not available for a number of countries (Cyprus, Estonia, Finland and Italy). As a result, the ratio of seriously injured to killed casualties was calculated for the remaining 21 countries; this was then averaged and an estimate of the number of seriously injured casualties, in those countries where the figures were not available, was obtained. This was done separately for 'all casualties' and 'car occupant casualties' to account for any difference between these groups. It should be noted there was large variation in the individual ratios for each country and hence, the average ratio may not be representative of the country in question; estimates obtained may be over or under representations of the true seriously injured casualty figure.

Table 41: Killed and seriously injured casualties in Germany, GB and Europe by casualty type, 2008 (Source: CARE database).

	Killed within 30 days		**Seriously injured**	
	All casualties	**Car occupant casualties**	**All casualties**	**Car occupant casualties**
Germany	4,477	2,368	70,644	30,589
Great Britain	2,538	1,250	26,034	10,643
EU-15	**25,420**	**12,497**	**225,990**	**96,075**
EU-27 (excluding Bulgaria & Lithuania)	**37,384**	**18,029**	**268,062**	**114,581**

Using the benefit proportions estimated for GB and Germany described in the sections above, European casualty data from CARE and simple scaling, upper and lower estimates of the benefit for Europe were made for each of the options (Table 42). The upper and lower estimates were obtained by scaling with the highest or lowest benefit proportion from either the GB or German analysis. The killed proportions were taken from the GB analysis only because it was only the GB analysis that estimated these proportions separately from the seriously injured proportions. Similarly, the proportions for Option 3b 'Full Width and PDB test fork effect only' were taken from the GB analysis only.

Table 42: Benefits for Europe for all options.

Option	No of car occupant casualties in EU27		% (No) of car occupant casualties			
	Killed	Seriously injured	Killed		Seriously injured	
			Upper	Lower	Upper	Lower
Option 1 'No change'	**18,029**	**114,581**	2.0%	1.8%	1.7%	0.1%
			361	325	1,948	115
Option 2 'Full width test'	**18,029**	**114,581**	6%	5%	12%	6%
			1,034	901	13,750	6,875
Option 3a 'Full width & PDB test all'	**18029**	**114581**	10%	9%	14%	7%
			1,810	1,623	16,041	8,021
Option 3b 'Full width & PDB test fork effect only'	**18029**	**114581**	7%	6%	11%	8%
			1,293	1,155	12,641	9,044

7 COSTS

The benefits predicted for GB, Germany and Europe above were converted in monetary values using the costs of killed, seriously injured and slightly injured road accident casualties published by the UK and German governments. Break-even costs, i.e. the cost per car for a cost / benefit ratio of one, were calculated by dividing the monetary value of the benefit by the number of new cars registered per year. These costs were compared with costs estimated in previous projects to give some idea of the cost effectiveness of the options analysed.

7.1 Previous Cost Analysis Studies

In previous studies cost analyses have been made, the results of which are summarised below:

- APROSYS: estimate of cost to improve restraint system for Full Width test [Cuerden 2006]
  - To meet R94 limits in Full Width test € 32 per car based on Fiat Bravo.
- Add collapsible steering column, degressive load limiter and double pretensioner
  - To meet FMVSS208 limits in FW test € 17 per car based on Fiat Bravo
- Add collapsible steering column and degressive load limiter

Note: Items such as a collapsible steering column and double pretensioner may be present already on many of today's vehicles.

- VC-COMPAT: estimate of cost to improve structural interaction for enhanced compatibility[Edwards 2007]
  - Add second load path € 102 per car
  - Add second load path and reinforce compartment € 222 per car
- EEVC WG13/21: estimate of costs to improve structure and introduce airbags for pole test [Edwards 2010]
  - Between € 297 and € 386 depending on original safety performance level of car
- NHTSA 2007: Final impact assessment to add oblique pole test [NHTSA 2007]
  - Assume add two or four sensor curtain airbag system
  - Between $ 243 (€ 182) and $ 280 (€ 210) ($ 1 = € 0.75€)

7.2 Costs for GB

The UK DfT published the following costs per casualty (Table 43) in 'Reported Road Casualties Great Britain: 2010 Annual Report' [RRCGB 2010].

Table 43: UK costs per casualty [RRCGB 2010]

		£ June 2009
Accident/casualty type	Cost per casualty	Cost per accident
Fatal	1,585,510	1,790,200
Serious	178,160	205,060
Slight	13,740	21,370
Average for all severities	47,740	68,320
Damage only	-	1,880

Using ACEA data [ACEA 2012] it was found that the number of registered cars in UK on average per year for 2008 to 2010 was 2,333,792 (Table 44).

Table 44: Number of new cars registered in UK 2008 - 2010.

Country	2008	2009	2010	Average
UK	2,485,258	2,222,542	2,293,576	2,333,792

From this information and an exchange rate of £1=€1.2, break-even costs for Options 2 and 3 were calculated for GB (Table 48).

Note: it was assumed that total number of casualties remained the same so the decrease in number of killed and seriously injured casualties equalled an increase in slightly injured casualties, the cost of which was taken into account in the calculation.

Table 45: Break-even costs for GB for Options 2 and 3.

Option	% (No) of car occupant casualties				Monetary Value (€M)		Break-even costs (€)	
	Killed		Seriously injured		Upper	Lower	Upper	Lower
	Upper	Lower	Upper	Lower				
Option 2 'Full width test'	6%	5%	12%	6%				
	60	52	943	694	299	235	128	101
Option 3a 'Full width & PDB test all'	10%	9%	14%	7%				
	105	93	1,231	885	441	350	189	150
Option 3b 'Full width & PDB test fork effect only'	7%	6%	11%	8%				
	75	67	1,086	777	356	280	152	120

7.3 Costs for Germany

German published monetary values for saving a casualty of fatal € 1,010,907, serious € 112,296 and slight € 4,437 [Bast 2011] were used for this calculation instead of the GB ones. These values are considerably less than the GB ones (Table 46). A probable cause of this is that the GB values contain a 'willingness to pay' element whereas the German values do not.

Table 46: Comparison of government published casualty costs for GB and Germany.

Casualty severity	GB Cost (€)	German cost (€)
Killed	1902612	1010907
Seriously injured	213792	112296
Slightly injured	16488	4437

Applying the same methodology as for GB and assuming that the number of new cars registered in Germany per year for 2008 to 2010 was 3,271,167 [Statistisches Bundesamt 2011], break-even costs for Options 2 and 3 were calculated for Germany, see Table 47.

Table 47: Break-even costs for Germany for Options 2 and 3.

Option	Break-even costs (€)	
	Upper	Lower
Option 2 'Full-width test'	175	84
Option 3 'Full-width & PDB test'	203	97

7.4 Costs for Europe

The number of new cars registered in the EU27 (excluding Bulgaria and Lithuania) average per year 2008-2010 was estimated to be 15,838,011 [ACEA 2012] (Table 48).

Table 48: Number of cars registered in EU27 excluding Bulgaria and Lithuania.

Country	2008	2009	2010	Average
Bulgaria	55,236	29,247	18,857	34,447
Lithuania	28,885	8,918	10,369	16,057
EU15	15,293,804	14,804,292	14,202,042	14,766,713
EU27*	16,730,630	15,793,939	15,140,977	15,888,515
EU27* (excluding Bulgaria and Lithuania)	16,646,509	15,755,774	15,111,751	**15,838,011**

*Data for Malta and Cyprus not available

Using this value, the ranges of the break-even costs for Options 2 and 3 for Europe were calculated using the benefits estimated for Europe in Section 6 and the highest (GB) and lowest (German) monetary values for saving a casualty.

Table 49: Break-even costs for Europe for Options 2 and 3.

Option	% (No) of car occupant casualties in EU27 (excluding Bulgaria and Lithuania)				Monetary Value (€M)		Break-even costs (€)	
	Killed		Seriously injured		Upper	Lower	Upper	Lower
	Upper	Lower	Upper	Lower				
Option 2 'Full width test'	6%	5%	12%	6%				
	1,034	901	13,750	6,875	4,663	1,649	294	104
Option 3a 'Full width & PDB test all'	10%	9%	14%	7%				
	1,810	1,623	16,041	8,021	6,579	2,498	415	158
Option 3b 'Full width & PDB test fork effect	7%	6%	11%	8%				
	1,293	1,155	12,641	9,044	4,932	3,963	311	250

7.5 Discussion and Conclusions

Comparing the costs estimated by previous projects with the break-even costs for Option 2 above shows the costs estimated by the APROSYS project for modifications to the restraint system are much lower. This indicates that the costs of introducing the improved restraint systems necessary to deliver the benefit predicted for Option 2 are likely to be less than the monetary value of the benefits, i.e. a cost benefit ratio of less than one. However, at present it is not known what vehicle restraint system changes would be needed to deliver the injury reduction assumed for this benefit analysis. It is likely that substantial changes will be needed, e.g. adaptive restraint systems. Also, it is not known what dummy performance limits will be needed in the Full Width test to enforce the fitment of appropriate restraint systems, and indeed whether or not the current HYBRID III dummy is sufficient for this purpose. More work is needed to address these issues but at present indications are that the benefits of implementing Option 2 should be greater than the costs.

8 DISCUSSION

It is interesting to note that, even though different injury reduction models had to be used for the GB and German analyses because of the different natures of the databases, the proportions calculated for the target populations and benefits were quite similar. The only significant difference of note was in the break-down of the target population. In the German data a larger proportion of the target population had injuries related to restraint performance issues and a smaller proportion had injuries related to the fork effect compared to the GB data (Figure 4.7 and Figure 5.5). It is believed that this difference is in the accident data because a great deal of care was taken to perform the GB and German analyses in a similar way although a somewhat subjective approach had to be used. It should be noted that because of this subjective approach there were some small differences, e.g. frontal tree collisions were mainly assigned to 'Fork effect' in the GB analysis but to 'Deceleration' or 'No issue' in the German analysis.

As an outcome of the German GIDAS analysis additional issues were identified, which may warrant further investigation in the future. These included the observation that often the front passenger injury severity was higher than the driver's even though the impact was on the driver's side and a large number of underride issues were seen in crashes of passenger cars against heavy goods vehicles.

Finally it should be noted that the dummy performance limits for a full width test need to be reviewed by future working groups in order to achieve the injury reduction assumed in the benefit analysis. It is likely that more stringent performance limits than the current R94 will be needed or indeed perhaps additional tests with different dummy sizes and/or tests at lower speeds with even more stringent performance limits. For reference, a non-exhaustive overview of dummy readings from full-width deformable barrier tests in the FIMCAR crash test data base is included in Annex B.

9 SUMMARY OF CONCLUSIONS

- For the benefit analysis it was assumed that the introduction of a full-width test with appropriate compatibility and dummy metrics has the potential to address the frontal impact issues under/override related to structural alignment and restraint related acceleration type injuries. Limited potential of the full-width test was expected for addressing fork effect issues. It was also assumed that the replacement of the ODB by the PDB/MPDB test procedure with an appropriate homogeneity metric had the potential to address the frontal impact issues under/override related to vertical load spreading, fork effect and low overlap as well as frontal force matching/compartment strength.
- The benefits of three potential changes to the frontal impact regulation were calculated for GB and Germany and scaled to give an indicative estimate for Europe.
  - For Option 1 'No change', a small benefit of about 2.0% or less of all car occupant Killed and Seriously Injured (KSI) casualties was estimated;
  - For Option 2 'Add FW test: Benefit of 5% to 12% of all car occupant KSI casualties was estimated. It was shown that this benefit consisted of:
    - Structural alignment (under/override related to structural alignment): 0.3% - 0.8%. However, it should be noted that the benefit related to structural alignment was likely to be under-estimated.
    - Restraint system (restraint related deceleration related injuries): 5% - 11%
- For Option 3 'Add FW test and replace ODB test with PDB test' 7% to 14% of all car occupant KSI casualties.
  - Note: Benefit percentages for Options 2 and 3 do not include the benefit of Option 1 'No change'.
- Break-even costs for options 2 and 3 were calculated. Comparison of these costs with costs estimated by previous projects indicated that the monetary value of the benefits of implementing Option 2 should be greater than the costs to modify the cars for restraint system changes. However, further work is needed to determine precisely what changes would be needed to deliver the injury reduction assumed for the benefit analysis and precisely what test configuration (in particular dummies) and performance limits would be needed to enforce these changes.

The following points should be noted:

The benefit was calculated assuming the implementation of complete assessment procedures. However, appropriate dummy assessment values and dummy selection were not addressed by FIMCAR and appropriate PDB/MPDB metrics are not yet established.

Possible further potential benefits from the definition of a common interaction zone related to truck underrun protection and roadside guard rails were not considered in the study.

The conclusions for the GB additional analysis that was performed were:

- The benefit of 'No change' for car occupant casualties injured in side impacts was estimated to be approximately 3 percent of all killed car occupant casualties and 2 percent of all seriously injured car occupant casualties.
- The target population for casualties in car side impacts in which the car was struck by another car which had improved compatibility ranged from 4 to 7 percent of all killed car occupant casualties and 4 to 6 percent of all seriously injured car occupant

casualties depending on whether just struck side or struck side and non-struck side occupants were assumed to experience benefit.

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12 GLOSSARY

AIS:	Abbreviated Injury Severity Scale, describing the mortality rate of an injury ranging from 0 (not injured) to 6 (medical treatment today impossible), AIS 1 injuries and sometimes also AIS 2 injuries are reported to be superficial; Injuries above a certain level are often described as AIS X+ (e.g., AIS 2+ meaning injuries with severity levels 2, 3, 4, 5 and 6). In the databases AIS 9 is often coded for unknown severity level
Deceleration injuries	injuries related to the restraint system caused by loading of the occupant by the seatbelt or airbag to decelerate him and prevent greater injuries by contact with other car interior structures. Deceleration injuries are sometimes referred to as 'restraint' or 'restraint related' injuries.
delta-v	velocity change following a collision
DRV:	driver
DV	delta-v
EES:	Energy Equivalent Speed describing the deformation energy by a velocity that would create this deformation with $E_{def} = ½\ m\ EES^2$
ETS:	Estimated Test Speed; test speed of the vehicle against a rigid fixed barrier that would cause the same deformation. Note: similar to EES.
FSP:	Front Seat Passenger
FPS:	Front Passenger Seat
FW:	Full-width test including FWDB and FWRB
HGV:	Heavy Goods Vehicle / large truck (within GIDAS study also including coaches and buses
KSI:	Killed or seriously injured people
MAIS:	Maximum AIS coded injury, i.e. the most severe injury
Mass ratio:	relationship between the mass of two vehicles with mass ratio larger than one meaning the opponent vehicle is heavier than the case vehicle
MPDB:	Movable Deformable Barrier test using the PDB barrier face
ODB:	Off-set Deformable test (used for current ECE R94)
PDB:	Progressive Deformable Barrier test
PSV:	Public Service Vehicle (buses and coaches)

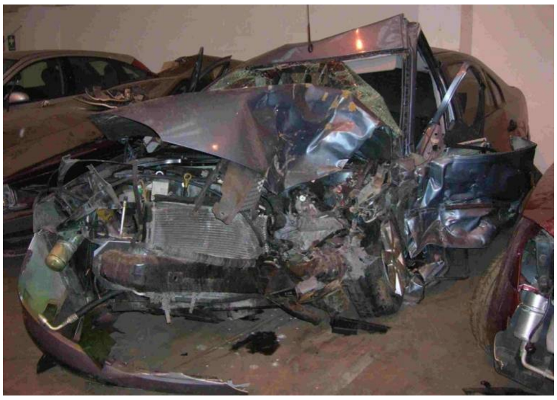
ANNEX A: EXAMPLE CASES

Examples of detailed case analyses to identify casualties in target population and estimate benefit of implementing Options 2 and 3 are given in the following.

Case Example 1 (CCIS data set: Structural interaction issue, over/underride): Ford Mondeo (2002) vs. Ford Mondeo (2001)

Accident description

Vehicle 1 (Mondeo 2002)



Vehicle 2 (Mondeo 2001)

Figure A.1: Frontal deformation of vehicles showing that the vehicles over/underrode each other.

The accident consisted of a head-on collision between a 2002 Ford Mondeo (vehicle 1) and a Ford 2001 Ford Mondeo (Vehicle 2). The overlap was estimated to be 50%. Other accident parameters are shown in Table A1.

Table A1: Mondeo vs. Mondeo accident parameters.

Parameter	Vehicle 1 (Mondeo 2002)	Vehicle 2 (Mondeo 2001)
ETS (km/h)	26	46
DV (km/h)	37	38
Intrusion	o/s (driver) None	o/s (driver) steering wheel 19cm lateral, 8 cm longitudinal Facia at knee contact area 18 cm A-pillar / top of facia 0 cm Footwell 5 cm

The 32 year old male driver in Vehicle 1 was seriously injured (MAIS 2, shoulder – principal injuries caused by seatbelt loading) and the 53 year old male driver in Vehicle 2 was fatally injured (MAIS 5, chest- principal injuries caused by contact with front intruding structure). Examination of the frontal deformation of the vehicles shows that they over/underrode each other in the collision – vehicle 1 overrode vehicle 2. This is seen from the vertical deformation profiles; there is more deformation lower down on vehicle 1 and less deformation higher up and vice-versa for vehicle 2.

Occupant injuries and benefit analysis

Vehicle 1 Driver MAIS 2

1. Displaced break to right clavicle (AIS2) *caused by seatbelt (belt webbing)*

Target population

It was considered that it was reasonable to assume that with better structural interaction and an improved restraint system the casualty injuries would have been less severe and hence this casualty was included in the target population for Options 2 and 3.

Benefit assessment

From application of injury reduction models for FW and PDB tests described in GB methodology section above.

FW test – structural alignment – no injury reduction Structural alignment will not be improved because vehicles in accident already have their structures in alignment with the common interaction zone, hence no benefit from this aspsect of the FW test.

FW test – improved restraint system – decrease injury to MAIS 1 (pessimistic and optimistic). Improved restraint system should reduce seatbelt loading.

PDB test all – structural interaction - no injury reduction because no intrusion related injuries (pessimistic), decrease injury to MAIS 1 due to improved deceleration pulse (optimistic).

PDB test fork effect only – no fork effect issue identified – no injury reduction.

Benefit

- Option 2 (FW) – MAIS 2 to 1 (pessimistic and optimistic).
- Option 3a (FW & PDB all) – MAIS 2 to 1 (pessimistic and optimistic).
- Option 3b (FW & PDB fork effect only) – MAIS 2 to 1 (pessimistic and optimistic).

Vehicle 2 Driver MAIS 5

1. Multiple rib breaks: left 1, 2, 5, 6 laterally, 5 - 10 posteriorly & right 4 - 8 posteriorly (with left haemothorax & bilateral pneumothoraces) (AIS5) *Caused by steering wheel (intruded)*
2. Massive retroperitoneal haematoma (AIS3). *Caused by seatbelt*
3. Rupture to spleen (AIS3). *Caused by seatbelt*
4. Rupture to left diaphragm producing communication between abdominal & thoracic cavities (AIS3). *Caused by seatbelt (belt webbing).*
5. Break to left clavicle (AIS2). *Caused by steering wheel (rim) (intruded)*
6. Extensive break to left posterior pelvis in region of sacroiliac joint with extensive (surrounding pelvic) haemorrhage (AIS3). *Caused by facia (intrusion)*
7. Break to left anterior pubic ramus, left superior & inferior pubic ramus and right superior pubic ramus (AIS2). *Caused by facia (intrusion).*
8. Haemopneumothorax (AIS5). *Caused by steering wheel rim. (intruded).*

Target population

It was considered that it was reasonable to assume that with better structural interaction, intrusion would have been less and the casualty injuries would have survived with less injuries and hence this casualty was included in the target population for Options 2 and 3.

Benefit assessment

From application of injury reduction models for FW and PDB tests described in GB methodology section above.

FW test – structural alignment – no injury reduction Structural alignment will not be improved because vehicles in accident already have their structures in alignment with the common interaction zone, hence no benefit from this aspect of the FW test.

FW test – improved restraint system – no injury reduction; improved restraint system will not reduce main injuries caused by intrusion.

PDB test all – structural interaction - MAIS 5 to 3 (pessimistic) and MAIS 5 to 2 (optimistic). Improved structural interaction should prevent intrusion and hence remove intrusion related injuries (pessimistic) and reduce deceleration induced injuries (optimistic).

PDB test fork effect only – no fork effect issue identified – no injury reduction

Benefit
- Option 2 (FW) – no injury reduction.
- Option 3a (FW & PDB all) – MAIS 5 to 3 (pessimistic), MAIS 5 to 2 (optimistic).
- Option 3b (FW & PDB fork effect only) – no injury reduction.

Case example 2: CCIS data set: Structural interaction issue (over/under-ride): Vauxhall Corsa (2002) vs. Mitsubishi Shogun (2003)

Accident description

Vehicle 1 (Corsa 2002)

Vehicle 2 (Shogun 2003)

Figure A.2: Frontal deformation of vehicles showing that the vehicles over/underrode each other.

The accident consisted of a head-on collision between a 2002 Vauxhall Corsa (vehicle 1) and a 2003 Mitsubishi Shogun (vehicle 2). The overlap was estimated to be 55%, the mass ratio 1.91. Other accident parameters are shown in Table A2.

Table A2: Corsa vs Shogun accident parameters.

Parameter	Vehicle 1 (Corsa 2002)	Vehicle 2 (Shogun 2003)
ETS (km/h)	46	33
DV (km/h)	53	28
Intrusion	Facia at knee contact area 19 cm A-pillar/top of facia 27 cm Footwell 11 cm	Facia at knee contact area 3 cm A-pillar/top of facia 1 cm Footwell 12 cm

The driver of vehicle 1 (Vauxhall Corsa 2002) was fatally injured (MAIS5) with principal injuries caused by contact with the steering wheel. The driver of vehicle 2 (Mitsubishi Shogun) was seriously injured (MAIS2) with principal injuries caused by contact with the footwell. Examination of the frontal deformation of the vehicles shows that they over/underrode each other in the collision – vehicle 2 overrode vehicle 1. This is seen from the vertical deformation profiles, there is much more deformation (and compartment intrusion) higher up on vehicle 1 and vice versa for vehicle 2.

Occupant injuries and benefit analysis

Vehicle 1 (Vauxhall Corsa)

The driver of vehicle 1 (49 year old male) sustained the following injuries:

- Flail chest on right (AIS4) caused by contact with the intruded steering wheel.
- # to right forearm (AIS2) caused by contact with the intruded A-Pillar.

- # to neck of right femur (as a result of knee into facia femur loaded, classed as facia) (AIS3) caused by contact with the intruded facia panel.
- Blood in subdural space – haemorrhage (AIS4) caused by contact with the intruded facia panel.
- Extensive subarachnoid haemorrhage (AIS3) caused by contact with the intruded facia panel.
- Extensive #s of both rib cages, particularly ribs 5-12 on right anteriorly & posteriorly with right haemothorax & bilateral haemothoraces (AIS5) caused by contact with the intruded steering wheel.
- Transection of spinal cord through T5/6 level (AIS5) caused by contact with the intruded steering wheel.
- # to C4 cervical spine (spinal cord uninjured at this level) (AIS2).
- Multiple surface lacerations to liver (AIS2) caused by contact with the intruded steering wheel.
- 9cm laceration to spleen (AIS2).

Target population

It was considered reasonable to assume that improved structural interaction would have reduced intrusion and hence injuries associated with contact with intrusion. Therefore The driver of vehicle 1 was included in the target population for Options 2 and 3.

Benefit

From application of injury reduction models for FW and PDB tests described in GB methodology section above.

- FW test - structural alignment improved – would help prevent under/override and remove intrusion related injuries (pessimistic)and reduce deceleration related injuries because of improved pulse (optimistic) (pessimistic and optimistic MAIS 5 to 2)
- FW test – improved restraint system - no decel pulse issue identified – no injury reduction
- PDB test (all) – improved structural interaction (over/underride) – remove intrusion related injuries (pessimistic) and reduce deceleration related injuries because of improved pulse (optimistic) (pessimistic and optimistic MAIS 5 to 2)
- Option 2 (full width) – MAIS5 to MAIS2 (pessimistic and optimistic).
- Option 3a (full width and PDB full) – MAIS5 to MAIS2 (pessimistic and optimistic).
- Option 3b (full width and PDB fork effect only) – MAIS5 to MAIS2 (pessimistic and optimistic).

<u>Vehicle 2 (Mitsubishi Shogun)</u>

The driver of vehicle 2 (29 year old male) sustained the following injuries:

- Comminuted # to posterior talus, left foot (AIS2) caused by footwell (intruded)
- # through anterior body of calcaneum, left foot (AIS2) caused by footwell (intruded)

Target population

Reasonable to assume that improved structural interaction (alignment) would have reduced footwell intrusion and hence injuries associated with contact with intrusion, hence casualty included in target population for Options 2 and 3.

Benefit

- FW test - structural alignment improved – would help prevent under/override and remove intrusion related injuries (pessimistic)and reduce deceleration related injuries because of improved pulse (optimistic) (pessimistic and optimistic MAIS 2 to 1)
- FW test – improved restraint system - no deceleration pulse issue identified – no injury reduction
- PDB test (all) – improved structural interaction (over/underride) – remove intrusion related injuries (pessimistic) and reduce deceleration related injuries because of improved pulse (optimistic) (pessimistic and optimistic MAIS 2 to 1)
- PDB test (fork effect only) – no fork effect issue identified – no injury reduction
- Option 2 (full width) – MAIS2 to MAIS1 (pessimistic and optimistic).
- Option 3a (full width and PDB full) – MAIS2 to MAIS1 (pessimistic and optimistic).
- Option 3b (full width and PDB fork effect) – MAIS2 to MAIS1 (pessimistic and optimistic).

Case example 3: CCIS data set: Frontal force mismatch / compartment strength: <u>Toyota Yaris (2008) vs Vauxhall Astra (2007)</u>

Accident description


Vehicle 1 (Yaris 2008) Vehicle 2 (Astra 2007)

Figure A.3: Deformations of vehicles showing much greater compartment deformation of Yaris compered to Astra showing frontal force matching / compartment strength compatibility problem.

The accident consisted of a head-on collision between a 2002 Vauxhall Corsa (vehicle 1) and a 2003 Mitsubishi Shogun (vehicle 2). The overlap was estimated to be 60%, the mass ratio 1.41. Other accident parameters are shown in Table A3.

Table A3: Yaris vs. Astra accident parameters.

Parameter	Vehicle 1 (Yaris 2008)	Vehicle 2 (Astra 2007)
ETS (km/h)	57	46
DV (km/h)	60	43
Intrusion	Steering wheel 0 cm vertical, 3 cm lateral, 14 cm longitudinal Facia at knee contact area 13 cm A-pillar/top of facia 16 cm Footwell 8 cm	No intrusion

The driver of vehicle 1 (Toyota Yaris) was seriously injured (MAIS3) with principal injuries caused by seatbelt and contact with facia/footwell. The driver of vehicle 2 (Vauxhall Astra) was seriously injured (MAIS2) with principal injuries caused by seatbelt and pedals Examination of the frontal deformation of the vehicles shows that although structural interaction was reasonable there was much greater compartment intrusion for the Yaris than the Astra. This indicates a frontal force matching / compartment strength problem.

Occupant injuries and benefit analysis

Vehicle 1 (Toyota Yaris)

The driver of vehicle 1 (29 year old female) sustained the following injuries:

- # posterior portion L 1st rib (AIS3) caused by seatbelt
- small apical L pneumothorax (AIS3) caused by seatbelt
- 3 part distal tibial # with a long spiral into shaft and medial malleolar fragment pilon # (AIS3) caused by footwell (intruded)
- comminuted # L proximal fibula (AIS2) caused by facia panel (intruded)

Target population

It was considered reasonable to assume that with improved frontal force matching intrusion would have been reduced and hence injuries associated with contact with intrusion. Also, with an improved performance of the restraint system the severity of the deceleration related injuries caused by the seatbelt would have been reduced. Therefore the driver of vehicle 1 was included in the target population for Options 2 and 3.

Benefit

From application of injury reduction models for FW and PDB tests described in main report above.

- FW test - structural alignment improved – no issue identified – no injury reduction.
- FW test – improved restraint system – reduce seatbelt related injuries to AIS 2 (pessimistic) 1 (optimistic) – however overall no MAIS injury reduction because of AIS2 injury caused by pedals.
- PDB test (all and fork effect only) – improved frontal force matching – reduce intrusion related injuries to AIS 1 and seatbelt related injuries to AIS 2 (optimistic only).
    - Option 2 (Full width) – no injury reduction (MAIS) because AIS 3 injury caused by intrusion
    - Option 3a (Full width & PDB all) – MAIS 3 to 2 (pessimistic) and MAIS 3 to 1 (optimistic)
    - Option 3b (Full width & PDB Fork effect only) – MAIS 3 to 2 (pessimistic) and MAIS 3 to 1 (optimistic)

Vehicle 2 (Vauxhall Astra)

The driver of vehicle 2 (55 year old male) sustained the following injuries:

- compression # L1 anterior superior endplate (AIS2) caused by seatbelt
- weber A # R fibula (AIS2) caused by pedals

Target population

Fibula AIS2 injury not caused by intrusion and unlikely to be reduced with an improved restraint system. However, thorax injury caused by seatbelt which improved restraint system should help reduce. Hence casualty included in target population for Options 2 and 3.

Benefit

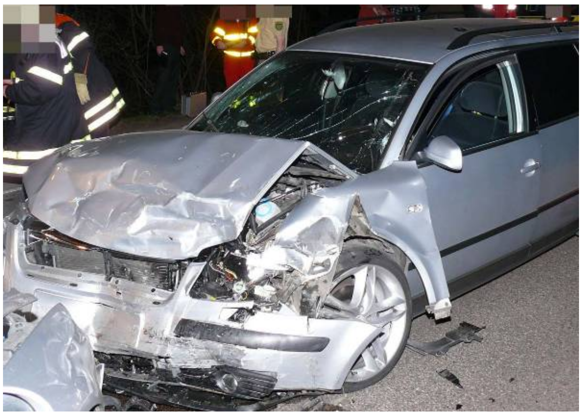
- FW test - structural alignment improved – no structural alignment issue identified so no injury reduction.

- FW test – improved restraint system – reduce thorax AIS 2 injury to AIS 1. However, no MAIS injury reduction because of fibula AIS 2 injury.
- PDB test (all) – improved structural interaction – no structural interaction issue identify so no injury reduction
- PDB test (all) – improved frontal force matching – no compartment intrusion so no improvement and hence no injury reduction
- PDB test (fork effect only) – improved frontal force matching – no compartment intrusion so no improvement and hence no injury reduction
- Option 2 (full width) – no injury reduction in terms of MAIS.
- Option 3a (full width and PDB full) – no injury reduction in terms of MAIS..
- Option 3b (full width and PDB fork effect) – no injury reduction in terms of MAIS.

Case Example 4 (GIDAS data set: Restraint performance issue):

VW Passat (2003) vs VW Passat (2006)

Accident description



Vehicle 1 (Passat 2003)

Vehicle 2 (Passat 2006)

Figure A.4: Frontal deformation of vehicles showing that the front structures hit aligned.

The accident consisted of a head-on collision between a 2003 VW Passat (vehicle 1) and a 2006 VW Passat (vehicle 2). The overlap was estimated to be >75%. Other accident parameters are shown in Table A4.

Table A4: Passat vs. Passat accident parameters.

Parameter	Vehicle 1 (Passat 2003)	Vehicle 2 (Passat 2006)
ETS (km/h)	42	43
DV (km/h)	48	47
Collision speed (km/h)	45	44
Intrusion	Passenger compartment stable	Passenger compartment stable

The 28 year old male driver in Vehicle 1 was seriously injured (MAIS 2, Sternum fracture – principal injuries caused by seatbelt loading), the 22 year old female front passenger was also seriously injured (MAIS 3, Contusion of superior lobe) and the 31 year old male driver in Vehicle 2 was slightly injured (MAIS 1, Bruise of soft tissue thorax and pelvis - principal injuries caused by seatbelt loading). Examination of the frontal deformations of both vehicles shows that cross and longitudinal beams hit each other in alignment. No important intrusions in the passenger compartments were investigated.

Occupant injuries and benefit analysis

Vehicle 1 Driver MAIS 2, male, 28 years old

1. Bruise of soft tissue Thorax (AIS 1) *caused by seatbelt (belt webbing)*
2. Distortion of cervical vertebrae NOS (AIS 1) *caused by body motion*
3. Fracture of sternum (AIS 2) *caused by seatbelt (belt webbing)*

Target population

It was considered that it was reasonable to assume that with an improved restraint system the casualty injuries would have been less severe and hence this casualty was included in the target population for Options 2 and 3.

Benefit assessment

From application of injury reduction models for FW and PDB tests described in methodology section above.

FW test – improved restraint system – decrease injury to MAIS 1 (optimistic). Improved restraint system should reduce seatbelt loading.

FW test – structural alignment – no injury reduction. Structural alignment will not be further improved because vehicles in accident already had their structures in alignment with the common interaction zone, hence no benefit from this aspect of the FW test.

PDB test – structural interaction - no injury reduction because no intrusion related injuries, decrease injury to MAIS 1 due to improved deceleration pulse (optimistic).

Benefit

- Option 2 (FW) – MAIS 2 to 1 (optimistic), no MAIS change (pessimistic)
- Option 3 (FW & PDB) – MAIS 2 to 1 (optimistic and pessimistic)

<u>Vehicle 1 Front Passenger MAIS 3, female, 22 years old</u>

1. Fracture of 20th vertebra (L1) (AIS 2) *caused by (not assigned)*
2. Fracture of 22nd vertebra (L3) (AIS 2) *caused by (not assigned)*
3. Fracture of sternum (AIS 2) *caused by (not assigned)*
4. Contusion of heart (AIS 1) *caused by seat belt (belt webbing)*
5. Contusion of superior lobe (AIS 3) *caused by seat belt (belt webbing)*
6. Rupture of intestinum jejunum (AIS 3) *caused by seat belt (belt webbing)*

Target population

It was considered that it was reasonable to assume that with an improved restraint system the casualty injuries would have been less severe and hence this casualty was also included in the target population for Options 2 and 3.

Benefit assessment

From application of injury reduction models for FW and PDB tests described in methodology section.

FW test – improved restraint system – decrease injury to MAIS 2 (optimistic). Improved restraint system should reduce seatbelt loading by the assumption of also avoiding submarining effects.

FW test – structural alignment – no injury reduction. Structural alignment will not be further improved because vehicles in accident already had their structures in alignment with the common interaction zone, hence no benefit from this aspect of the FW test.

PDB test – structural interaction - no injury reduction because no intrusion related injuries, decrease injury to MAIS 2 due to improved deceleration pulse (optimistic).

Benefit

- Option 2 (FW) – MAIS 3 to 2 (optimistic and pessimistic)
- Option 3 (FW & PDB) – MAIS 3 to 2 (optimistic and pessimistic)

<u>Vehicle 2 Driver MAIS 1, male, 31 years old</u>

1. Bruise of thoracic soft tissue (AIS 1) *caused by seat belt (belt webbing)*
2. Bruise of pelvic soft tissue (AIS 1) *caused by seat belt (belt webbing)*
3. Distortion of cervical vertebrae NOS (AIS 1) *caused by body motion*
4. Abrasion of hands (each AIS 1) *caused by (not assigned)*

Target population

This casualty was not included in the target population because it was not believed that additional compatibility measures (improved restraint system, structural interaction, etc.) would have decreased the level of MAIS 1 (slightly injured) to MAIS 0 (uninjured).

Case Example 5 (GIDAS data set: Small Overlap as compatibility issue):

<u>Ford Focus Turnier (2004)</u>

Accident description

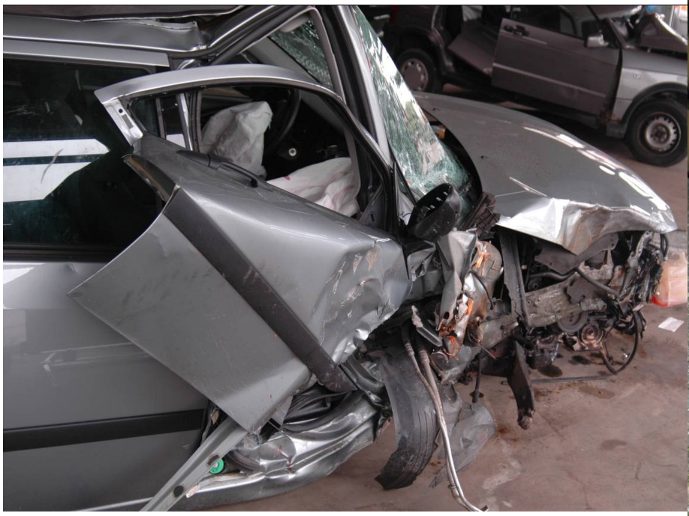


Figure A.5: Frontal deformations (left) of the vehicle hitting a tree (right).

The accident consisted of a small overlap collision between a Ford Focus (2004) and a tree located on the pathway. The driver left the road (light left bend) due to the speeding to the right side. The driver drove under the influence of alcohol. The overlap was estimated to be <25%. Other accident parameters are shown in Table A5.

Table A5: Ford Focus accident parameters.

Parameter	Vehicle 1 (Focus 2004)
ETS (km/h)	63
DV (km/h)	49
Collision speed (km/h)	76
Intrusion	Deformation of the right front including e.g. a-pillar, sill, door, partly dashboard, windscreen and roof

The 37 year old male driver in Vehicle 1 was seriously injured (MAIS 2, Scull-brain-trauma – principal injuries caused by the contact with the windscreen). The examination of the frontal deformations of the vehicle shows that the longitudinal beams were not hit in a sufficient manner and hence, the car was ripped on the right side, the compartment collapsed and started to rotate. Intrusions were investigated on the front passenger side within the compartment (seat was not used) and partly on the driver's side.

Occupant injuries and benefit analysis

<u>Vehicle 1 Driver MAIS 2, male, 37 years old</u>

1. Laceration (contusion wound) of scalp (AIS 1) *caused by contact with windscreen*
2. Laceration of forehead (AIS 1) *caused by contact with windscreen*
3. Scull-brain-trauma (AIS 2) *caused by (not assigned)*

Target population

It was considered that it was reasonable to assume that with an improved structural interaction (compartment integrity) the casualty injuries would have been less severe and hence this casualty was included in the target population for Options 2 and 3.

Benefit assessment

From application of injury reduction models for FW and PDB tests described in methodology section above.

FW test – improved restraint system – no injury reduction. Restraint system already worked well, though the forward displacement of the occupant might be restrained better.

FW test – structural alignment – no injury reduction (pessimistic and optimistic) because structural alignment will not be further improved. The vehicle in this accident had its structures in alignment with the common interaction zone, which would not have further benefit in this case.

PDB test – structural interaction - decrease injury to MAIS 1 (optimistic and pessimistic) because the (M)PDB test could lead to an improvement of the compartment integrity of this car and hence forward the loadings more effectively.

Benefit

- Option 2 (FW) – no MAIS change (optimistic and pessimistic)
- Option 3 (FW & PDB) – MAIS 2 to 1 (optimistic and pessimistic)

ANNEX B: FULL-WIDTH TEST PERFORMANCE LIMITS

To start to investigate the issue of what dummy performance limits will be needed in the Full Width test to enforce the fitment of appropriate restraint systems (those capable of delivering the injury reduction assumed by the injury reduction model used in this benefit analysis) dummy injury values for full width deformable barrier (FWDB) tests in the FIMCAR test database were compared to current regulatory performance limits.

A summary of the UN-ECE Regulation 94 and US FMVSS 208 performance limits are shown in the following table for reference.

Table B1: Summary of UN ECE R94 and US FMVSS208 performance limits.

Criteria	**R94 Limit**	**FMVSS208 Limit**	
	50^{th} %tile	**50^{th} %tile**	**5^{th} %tile**
HIC_{36}	1000	1000	
HIC_{15}		700*	700
Head Resultant Acceleration (3 ms excedence)	80g		
Neck Extension Moment	57 Nm		
Neck tension +Z	Excedence corridor 3.3 kN @ 0 ms 2.9 kN @ 35 ms 1.1 kN @ ≥ 60 ms	4.17 kN	2.620 kN
Neck shear X	Excedence corridor 3.1 kN @ 0 ms 1.5 kN @ 25-35 ms 1.1 kN @ ≥ 45 ms		
Neck compression –Z		4.00 kN	2.520 kN
N_{ij}		1.0	1.0
Chest Deflection	50 mm	63mm	52 mm
Viscous Criterion	1.00		
Chest acceleration (3 ms excedence)		60g	60g
Femur Compression	9.7 kN	10.0 kN	6.805 kN
Knee Displacement	15 mm		
Tibia Compression	8 kN		
Tibia Index	1.3		

*HIC_{15} used for advanced airbags generally fitted to vehicles 2004+

Dummy injury criteria values normalised to the UNECE Regulation 94 performance limits for the FWDB tests in the FIMCAR test database are shown in Figures B.1 to B.4. All test results shown had a test speed of 56 km/h. Noting that the UN-ECE Regulation 94 limits are in general more stringent than the US FMVSS 208 ones and that some of the cars in the FIMCAR test database are quite old, (e.g. Small Family Cars 1 and 2 are model years 2004) and the majority of them still meet the performance limits with relative ease; in order for a prospective full width test to enforce the fitment of improved restraint systems that will deliver the benefit estimated in this work, it is likely that more stringent performance limits than the current R94 will be needed or indeed perhaps additional tests with different dummy sizes and/or tests at lower speeds with even more stringent performance limits.

For reference it is interesting to note:

- Chest compression 50 mm (100% of R94 performance limit) equates to a 50% risk AIS 3+ injury
- Chest compression 22 mm (44% of R94 performance limit) equates to a 5% risk AIS 3+ injury

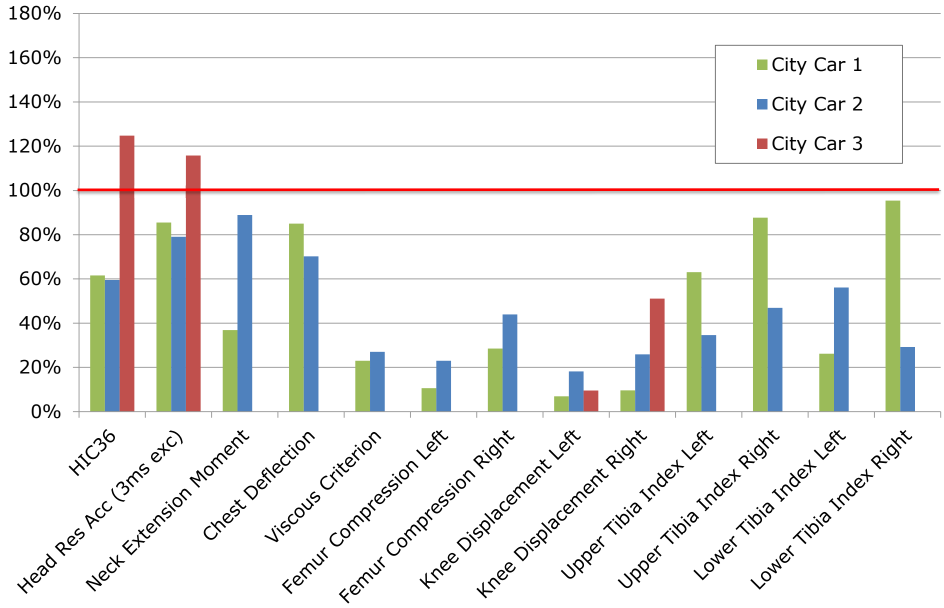


Figure B.1: Dummy injury criteria values for FWDB tests in FIMCAR test database (City Cars).

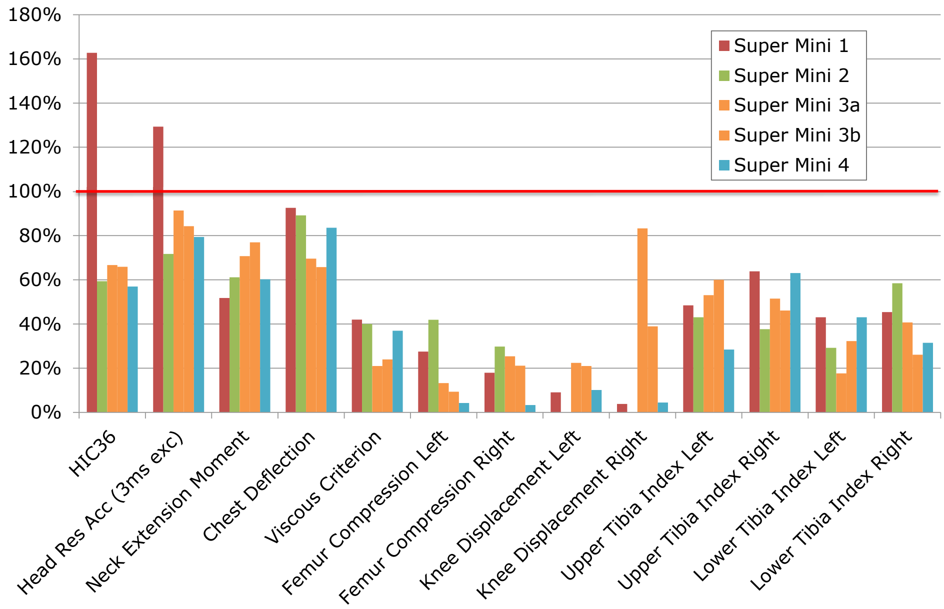


Figure B.2: Dummy injury criteria values for FWDB tests in FIMCAR test database (Super Minis).

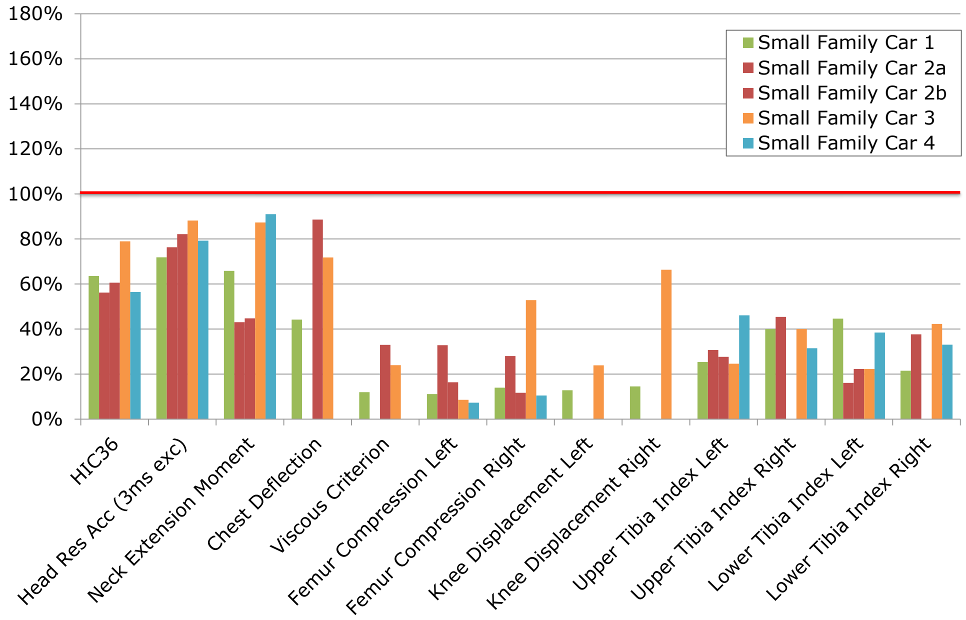


Figure B.3: Dummy injury criteria values for FWDB tests in FIMCAR test database (Small Family Cars).

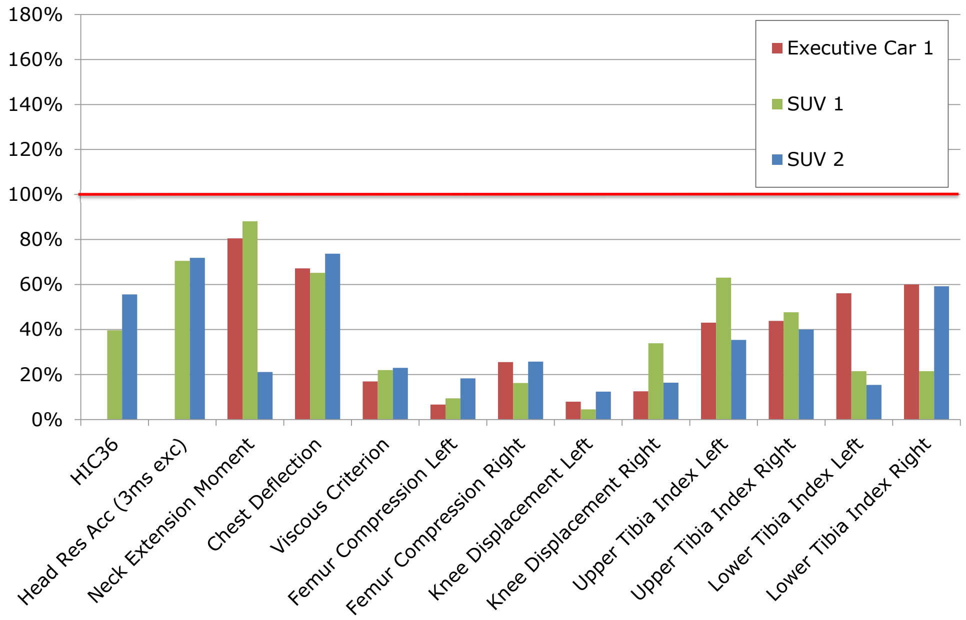


Figure B.4: Dummy injury criteria values for FWDB tests in FIMCAR test database (Executive Car and SUV).

Mathias Stein, Roberto Puppini, Peter Sandqvist

SEVENTH FRAMEWORK PROGRAMME

FIMCAR
XIV – Potential of Simulation Tools towards the Evaluation of Compatibility

FIMCAR

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

For the assessment of vehicle safety in frontal collisions compatibility (which consist of self and partner protection) between opponents is crucial. The use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

This report reviews the use of Virtual Testing (VT) in today's European vehicle and product type approval, and the on-going work for future implementation of VT in vehicle type approval and rating. The modelling requirements and validation process are discussed both regarding barrier models and car models. Combined with the experience from the use of simulation tools in the FIMCAR project, a 4-step roadmap for implementation of VT tools in the compatibility development is proposed.

Step 1

2013-2020: further evolution of GCMs concept (Generic Car Models) and consequent availability of first agreed/recognised reference VT model family for regulatory and/or rating application, with associated definition of verification and validation procedures. Convergence towards PGCMs concept (Parametric Generic Car Models) for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models are then capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020-2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly i.e. through indicators like OLC (Occupant Load Criterion) or other similar criteria as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted for type approval model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025-2030: first full vehicle-crash regulations (type approval and even self-certification) for car-to-car compatibility based on full VT (structural behaviour and dummy biomechanical response based on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030-2040: VT maturity reached, with type approval based on full system simulations (structural and biomechanical behaviour included, with human body models (HBM) as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the protocol).

1 INTRODUCTION

1.1 FIMCAR Project

For the real-life assessment of vehicle safety in frontal collisions, the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches have been identified as the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to analyse the potential of simulation tools towards the evaluation of compatibility. The report reviews the on-going activities in Europe regarding implementation of simulation tools in type approval- and rating procedures, and analyse/discuss how to implement compatibility into this on-going process.

1.3 Structure of this Deliverable

This report starts with an overview of activities towards Virtual Testing before and parallel to the FIMCAR project. This review is followed by a summary of the FIMCAR experience with numerical simulation w.r.t. structural assessment of cars with a focus on the FIMCAR car models used. Furthermore general requirements on models for Virtual testing (i.e., model verification and validation) are discussed. Chapter 4 presents a proposal how to assess frontal impact compatibility based on Virtual Testing. Finally this proposal is discussed w.r.t. to the road map presented by the IMVITER project that was running in parallel to the FIMCAR project.

2 BACKGROUND

2.1 Historical Evolution

Recently, changes in the EC type approval process related to the implementation of Virtual Testing (VT) have been introduced, so that now an appropriate regulatory framework is available to gradually implement the use of the numerical simulation for a wider variety of current and new regulatory acts. This situation in Europe is the result of intensive work conducted on the subject mainly in the last decade, with a special attention paid to the automotive safety aspects. The following list provides a historical review of the main activities to apply simulations in regulatory activities.

2001 - EU FP5 Project VITES (Virtual Testing for Extended vehicle passive Safety) starts to pave the way by evaluating the potential use of VT in regulations (Development of virtual testing procedures, guidelines and objective criteria for the evaluation of numerical models quality, including corresponding software tools – 3 years duration)

2002 – A technical working group (CEN/TC226/WG1/TG1/CME) was initiated in 2002 to investigate the use of computer simulations for the type approval of road equipment, specifically regulation EN-1317.

2004 - EU FP6 Integrated Project APROSYS (Advanced PROtection System) continues the studies on the subject with the aim to develop possible approaches and deliver practical demonstrators (Sub Project 7 on Advanced Virtual testing – 5 years duration). First Generic car Model versions (GCMs) are developed and used within this project.

2004/2005 – ISO TC22/SC10 WG4 and EEVC Working Group 22 on Virtual Testing are established

2005 - 'CARS 21 High Level Group' considers that the introduction of VT can provide more flexibility and reduce costs. The Group proposed to replace 38 EC directives with international UN/ECE regulations without any loss in the level of safety and environmental protection. Furthermore, it identified also 25 directives and UN/ECE regulations where self-testing and virtual testing could be introduced to reduce costs for industry. In particular it recommended introducing virtual testing in the following directives:

77/389/EEC (towing hooks)

77/649/EEC (forward vision)

78/318/EEC (wash/wipe for geometric requirements)

78/549/EEC (wheel guards)

92/114/EC (external projections of cabs)

(1)UNECE R-21 (for the geometric requirements of interior fittings)

UNECE R-26 (exterior projections)

UNECE R-46 (for the field of rear vision)

UNECE R-48 (installations of lighting)

UNECE R-55 (couplings; only with regard to geometric requirements)

2007 - Article 11 (3) of Directive 2007/46/EC: provides the possibility to use VT for regulatory purposes.

2008 - In order to go ahead with the recommendations of CARS 21 in the area of regulatory simplification, the Technical Committee – Motor Vehicles (TCMV) in its 4th meeting, sets up a calendar for a Sub-Group made of Stake-holders with the purpose of bringing forward a structured proposal on the implementation of VT before end of 2009.

2009 – The Sub-Group starts working with the initial list proposed in the final report of CARS 21. Physical phenomena addressed in the initial list were only pure geometric requirements.

2009 – At the APROSYS Final Event, demonstrators of possible approaches about implementation of VT in regulations/ratings are presented, with a special attention paid to pedestrian protection applications.

2009 – IMVITER Kick off meeting. The project aims to help and support in the definition of upcoming virtual type approval procedures. It was agreed to address three levels of complexity regarding the physical phenomena involved in each test. Physical phenomena are addressed in the initial list of pilot cases, from static (towing hook and seat belt anchorages) to complex dynamic tests (pedestrian head and leg form impacts).

2009 – There is a legislative proposal which collects the work of the Sub-Group of TCMV. In this proposal the number of cases and the physical phenomena involved has increased. Physical phenomena in the final list: pure geometric requirements, static and also dynamic cases.

2009 – FIMCAR kick-off meeting: within the project, a second generation of GCMs is developed for the virtual study of compatibility aspects, together with Parametric Car Models (or PCMs); numerical simulations involving such car models are extensively used to support definition and refinement of new proposals of frontal impact test configurations (through car-to-barrier and car-to-car numerical simulations).

2010 – COMMISSION REGULATION 371/2010 replaces Annexes V, X, XV and XVI to Directive 2007/46/EC, including the lists of Regulatory Acts for which a manufacturer may be designated as technical service and the conditions required to virtual and self-testing methods.

2011 – ISO releases new technical documents developed by the CEN/TC226/TG1/WG1/CME group describing the requirements for numerical simulations in type approval of road equipment covered in EN-1317.

2012 – IMVITER Final Event: the results of the project, on the four selected pilot cases, are presented to the public. These include also a roadmap for VT implementation in regulations.

2.2 Review of CAE in Vehicle and Product Type Approval/Rating

In the automotive sector, the following regulations/standards provide for the possibility for applying numerical simulation (or Virtual Testing) results:

ECE Regulation 66: Uniform provisions concerning the approval of large passenger vehicles with regard to the strength of their substructure.

EN-1317: Road restraint systems: Proposal for approving certain products by simulation using grading system identifying the combination of testing and simulation used in the type approval.

ISO 13232: Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles.

Directive 2007/46/EC: Framework directive for motor vehicles type approval and EC Regulation 371/2010 (Annexes V, XVI)

The last Directive (dated 5 September 2007) establishes a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles and, together with the Commission Regulation (EU) No 371/2010 of 16 April 2010, opens the door to use computer simulations, instead of conducting physical tests, for the type approval process. In particular, the ANNEX XVI (Specific conditions required from virtual testing methods) describes the general requirements that need to be satisfied when virtual testing is used. Within its Appendix 1, general conditions required from virtual testing methods are fixed:

- The virtual test pattern: a common scheme shall be used as basis structure for describing and conducting Virtual Testing;
- Fundamentals of computer simulation and calculation: Mathematical model, Validation process of the mathematical model and Documentation;
- Tools and support: access to appropriate software and respect of confidentiality.

Within Appendix 2, Specific conditions concerning virtual testing methods are recalled:

- List of regulatory acts: currently, Virtual Testing can be used mainly for geometrical related issues and identification of test conditions. Typically the geometrical prescriptions are verified virtually through CAD. CAE can be used for some quasi-static loading cases (e.g. towing hooks, front underrun protection systems) and for one dynamic load case (buses and coaches rollover). In the following, the tables contained in Appendix 2 are presented (Table 1 to Table 3).

Table 1: List of regulatory acts indicated in EC Reg. 371/2010-Appendix 2.

1. **List of regulatory acts**

No	Regulatory act reference	Subject
3.	Directive 70/221/EEC	Fuel tanks/rear protective devices
6.	Directive 70/387/EEC	Door latches and hinges
8.	Directive 2003/97/EC	Indirect vision devices
12.	Directive 74/60/EEC	Interior fittings
16.	Directive 74/483/EEC	Exterior projections
20.	Directive 76/756/EEC	Installation of lighting and light signalling devices
27.	Directive 77/389/EEC	Towing hooks
32.	Directive 77/649/EEC	Forward vision
35.	Directive 78/318/EEC	Wash/wipe
37.	Directive 78/549/EEC	Wheel guards
42.	Directive 89/297/EEC	Lateral protection
49.	Directive 92/114/EEC	External projections of cabs
50.	Directive 94/20/EC	Couplings
52.	Directive 2001/85/EC	Buses and coaches
57.	Directive 2000/40/EC	Front underrun protection

Table 2: Specific conditions for VT methods, from EC Reg. 371/2010-Appendix 2.

Specific conditions concerning virtual testing methods

1. **List of regulatory acts**

	Regulatory act reference	Annex and paragraph	Specific conditions
3.	Directive 70/221/EEC	Annex II (Rear underrun protection) Point 5.4.5.	
6.	Directive 70/387/EEC	Annex II Point 4.3.	
8.	Directive 2003/97/EC	Annex III All provisions in Sections 3, 4 and 5.	Prescribed fields of vision of rear-view mirrors.
12.	Directive 74/60/EEC	Annex I All provisions in Section 5 (Specifications).	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.
		Annex II	Determination of the head-impact zone.
16.	Directive 74/483/EEC	Annex I All provisions in Section 5 (General specifications) and Section 6 (Particular specifications).	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.
20.	Directive 76/756/EEC	Section 6 (Individual specifications) of UNECE Regulation No 48.	The test drive provided for in Point 6.22.9.2.2 shall be performed on a real vehicle.
		Provisions of Annexes 4, 5 and 6 to UNECE Regulation No 48.	
27.	Directive 77/389/EEC	Annex II, Section 2	
32.	Directive 77/649/EEC	Section 5 (Specifications) of Annex I.	
35.	Directive 78/318/EEC	Annex I	Point 5.1.2. Measurement of the swept area only.
37.	Directive 78/549/EEC	Section 2 (Special requirements) of Annex I	
42.	Directive 89/297/EEC	Annex I Point 2.8.	Resistance under a horizontal force and deflection measurement.
49.	Directive 92/114/EEC	Annex I All provisions in Section 4 (Specific requirements). Regarding N_1 vehicles, the provisions referred to in item 16 of this Appendix shall apply.	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.

Table 3: Specific conditions for VT methods, from EC Reg. 371/2010-Appendix 2 (cont. of Table 2).

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	Regulatory act reference	Annex and paragraph	Specific conditions
50.	Directive 94/20/EC	Annex V "Requirements for mechanical coupling Devices"	All provisions of Sections 1 to 8 included.
		Annex VI Point 1.1.	Strength tests on mechanicals couplings of simple design may be replaced by virtual tests.
		Section 4 of Annex VI "Testing of mechanical coupling devices"	Points 4.5.1. (Strength test), 4.5.2. (Resistance to buckling) and 4.5.3. (Resistance to bending moment) only.
52.	Directive 2001/85/EC	Annex I	Point 7.4.5. Stability test under the conditions specified in the Appendix to Annex I.
		Annex IV Strength of superstructure	Appendix 4 — Verification of strength of the superstructure by calculation.
57.	Directive 2000/40/EC	Section 3 of Annex 5 to UNECE Regulation 93.	Resistance under a horizontal force and deflection measurement.

In Appendix 3, the Validation process is outlined, through the use of a general flowchart (see Figure 2.1).

Validation process

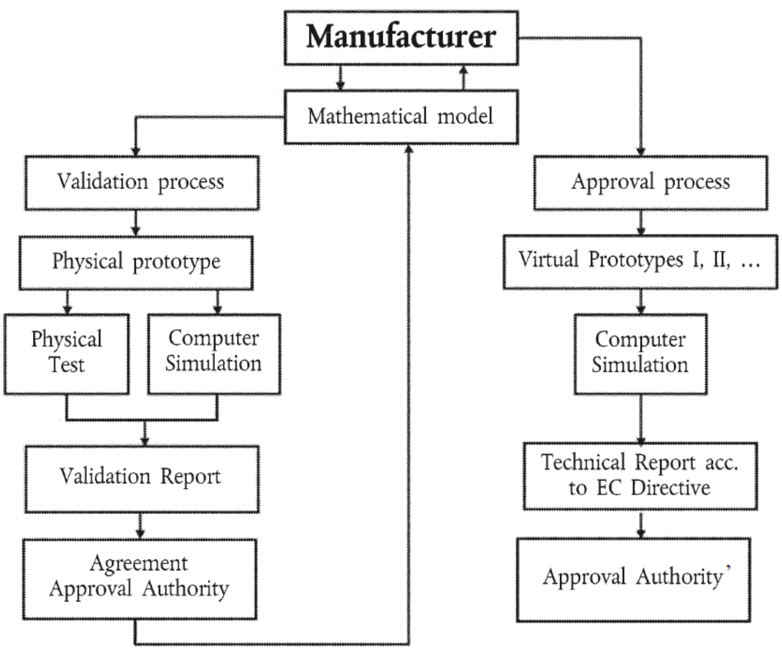

Figure 2.1: The general flow chart as defined within EC Reg.371/2010-Appendix 3.

Despite the given reference, this flowchart, together with the other general conditions required from virtual testing methods contained in ANNEX XVI of EC Directive 371/2010 [EC 2010] leaves several questions open, e.g. [Cordero 2012]:

- Does the manufacturer have to give a simulation model to the Technical Service? (Confidential information is included in simulation models!)

- Does the Technical Service have the necessary code(s)?
- How are simulation models predictability assessed?
- What differences between simulation model predictions and test results can be acceptable?
- Is a physical prototype really necessary?
- What is the benefit of VT if both test and simulations are to be conducted?
- What kind of test should be carried out? Do the same parameters need to be measured for validation purposes?
- Who should run the model?
- Which codes can be used? Commercial or in-house developed ones?

The IMVITER project worked on all these aspects and generated a step forward in terms of general procedural flow chart, detailed flow charts and corresponding written virtual testing procedures for type approval, by applying them on a selection of regulatory pilot cases, including pedestrian protection (head and leg form impacts) as the most complex dynamic load case.

More details about these evolutionary steps are given in Chapter 3.

3 SIMULATION TOOLS IN CRASH TESTING

3.1 Modelling Requirements

In general, a model is used to describe a specific and limited image of the real world. Two main characteristics can be found in a model: abstraction and idealisation. Thereby abstraction is the process of reducing unimportant details and idealisation is the process of isolating the important details. This is typically referred to as simplification process. Often the purpose of a model is the variation of parameters to investigate their influence on a system's response and to get a common understanding of specific mechanisms. To be sure that the model is suitable, a model has to be verified and validated. Thereby verification is the process of confirming the approach in which the model was created. Within the verification process the limits of a model and the intended field of applications have to be defined. After the modelling process has finished, a confirmation is needed to ensure that the model behaviour is the same as the original or at least comparable to it. This process is called validation. Only if these requirements are fulfilled the model provides verified and validated responses.

3.2 FIMCAR Car Models

Within the FIMCAR project two different modelling approaches for the development of FE car models were used. The GCM (Generic Car Models) were developed by CRF (Centro Ricerche FIAT S.C.p.A.) and the PCM (Parametric Car Models) developed by TUB (Technische Universität Berlin). The two types of models are available for three different crash solvers: LS-DYNA, PAM Crash and RADIOSS. In this way, it is possible to include the detailed car models of the OEMs (which are partners of the consortium) into the virtual test program. A short overview about the two modelling approaches will be given in the following sections. More details can be found in [Stein 2013/2].

3.2.1 GCM - Generic Car Models

The GCMs used in FIMCAR were derived from the GCMs developed by CRF within the research project APROSYS [Puppini 2009], through the implementation of huge modifications and improvements. In total five different models of three different vehicle classes (super mini, small family car and executive) were generated (see Figure 3.1). Two additional variants, with respect to the original architectures of super mini and small family car, were in fact introduced by the addition (super mini) or removal (small family car) of a lower load path.

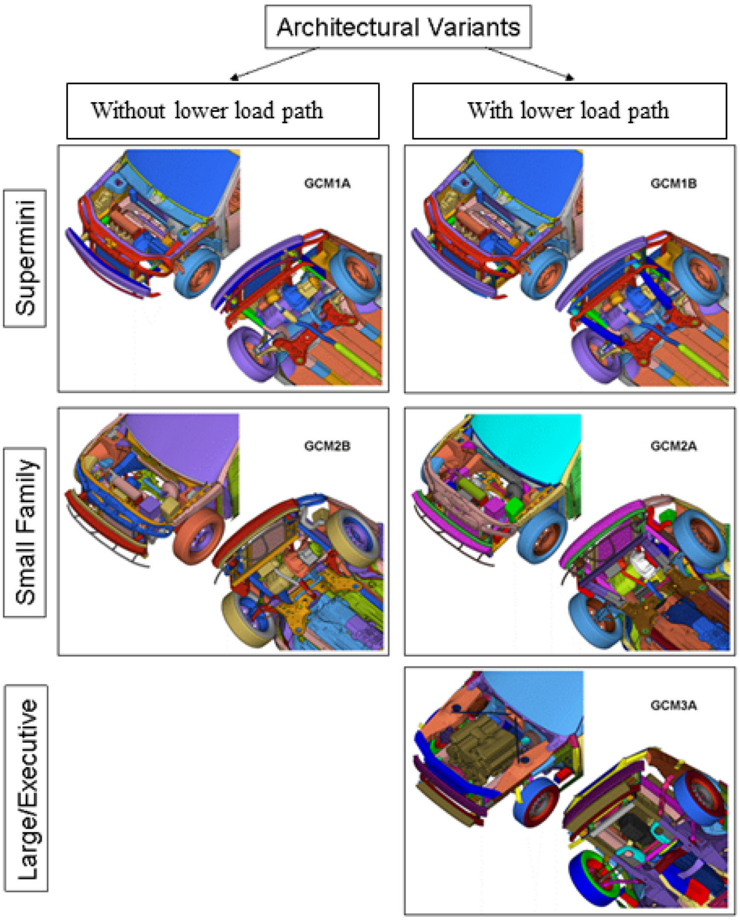

Figure 3.1: Architectural variants of GCMs.

The modelling was controlled by the following two main parameters: high level of detail (comparable to models of OEMs) and a generic topology of structures and parts of typical vehicles that can be found on the roads of the corresponding vehicle class. To fulfil the first requirement especially the front structures of the GCMs were modelled with fine mesh. Thus the models consist of about 600,000 elements. Although the structures are generic they are modelled to ensure realistic (i.e. representative of the European fleet) crash behaviour with respect to crash pulse, intrusion behaviour, energy absorption management and collapse modes.

The validation of the GCMs was performed for the US NCAP (rigid wall, 56 km/h, 100% overlap) and old ams (rigid wall, 55 km/h, 50% overlap, 15° wall inclination as conducted by the German automotive magazine “auto motor und sport”) configuration.

The main tasks of the GCMs within FIMCAR were to analyse the crash behaviour in the different frontal impact test configurations, to compare these results with responses from car-to-car simulations and to serve as common bullet vehicles against the OEM models.

3.2.2 PCM – Parametric Car Models

To investigate the influence of different front structure topologies and the impact of the assessment metrics to the front structures the PCMs were developed to overcome the aims of structural interaction. Normally to modify the structure of a finalised FE model is a complicated and time consuming exercise. Morphing tools or manual transformations of the mesh is time consuming and can cause numerical instability. To avoid these problems the PCMs approach uses an implicit parametric design of one CAD model that allows fast modifications of the structures. In this way, position as well as shape and size of the most important crash structures can be changed in an efficient way. Finally, an automatic mesh algorithm generates meshes and additional FE information needed to create computable FE models without further pre-processing [Stein 2011].

In contrast to the GCMs, one of the main requirements of the PCMs was the shorter calculation time. To comply with this, the PCMs were simplified. For example, all parts of the powertrain were merged to one rigid part, and crash relevant parts like cross beam, longitudinal side members and sub frame were modelled with respect to realistic crash behaviour (see Figure 3.2)

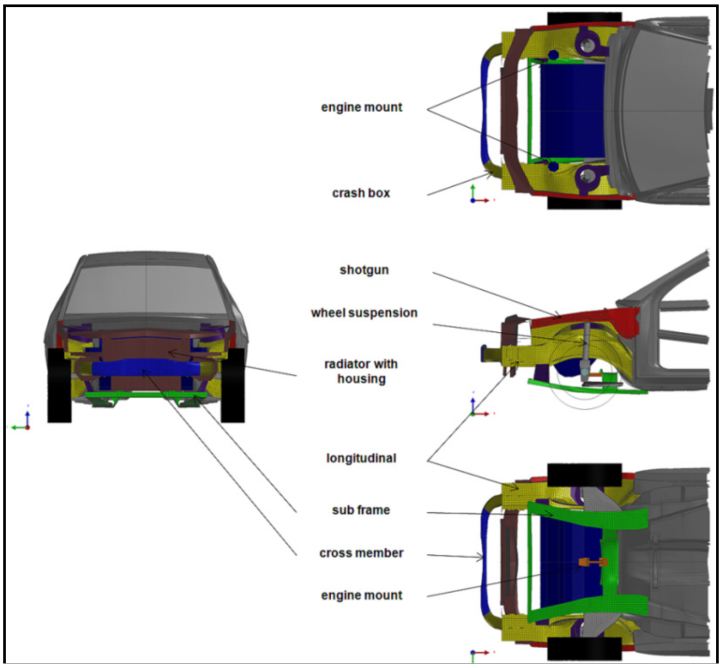

Figure 3.2: Front end structures of the PCMs.

During the first part of the FIMCAR project, three different vehicle classes (super mini, large family car and executive) were modelled. To reduce the computational effort, the mesh size was set to an edge length of 15 mm. The final number of elements is about 200,000 for each vehicle model.

The models were validated for the US NCAP configuration (rigid wall, 56 km/h, 100% overlap), where the crash pulse of the compartment was the main criterion. The pulses were compared (duration, peak and average deceleration) with real crash pulses of cars of the corresponding vehicle class.

The main tasks of the PCMs within FIMCAR are sensitivity analyses of the topology of structures in car-to-car crashes and robustness analyses of the test configurations and their corresponding assessment metrics.

3.2.3 Requirements for Vehicle Models

Both modelling approaches are results from the definitions given in Chapter 3.1. Regarding the intended field of applications the GCM approach should allow in-depth analyses of the structural interaction of the main EAS (Energy Absorbing Structures) and the under bonnet components. Due to the high level of detail w.r.t. the number of different modelled components and their connections to each other, the number of models is fixed (in total 5 different GCMs were available within FIMCAR). To overcome this limitation the PCMs were simplified vehicles based on a full parametric CAD model that allows fast design changes to analyse the influence e.g. of the topology of the EAS. Even though there are big differences between the two approaches, common requirements were used to create the models. On the one hand, the same validation criteria were used. Typical characteristics like acceleration pulse and force-deflection curves were used to generate a crash behaviour of the corresponding vehicle classes, see [Stein 2012]. On the other hand, model specific parameters in particular the mesh size (10mm – 15mm) were defined to ensure the interaction of GCMs and PCMs with the detailed models of the OEMs. Furthermore, both models guarantee numerical stability at least for the crash scenarios used for the validation process.

However, no common agreed procedure was used for verification and validation of the models. The following section summarises some recommendations of requirements for future modelling of vehicles for use, amongst other, within legislative framework.

3.2.4 Future Requirements for Vehicle Models

Taken into account the great efforts currently on-going in the field of VT it seems to be merely a matter of time until standardised vehicle models will be used to extend today's crash regulations. W.r.t the experiences made within FIMCAR the combination of both GCM and PCM approaches seems to be promising to provide vehicle models that can be used to overcome limitations of solver dependent FEM models as well as models of different manufactures, see Chapter 3.4.

The following requirements for a combination of GCMs and PCMs can be used for the verification and validation process:

Verification:

- Topology of main EAS as well as crash relevant parts (e.g. engine, wheels, radiator and cooler) can be derived from the VC COMPAT and IMPROVER structural databases. In that way, different generic vehicle classes can be created to represent the actual European vehicle fleet in terms of mass, dimensions and structural concepts. A parametric design of either a CAD model or an FEM model provides the possibility to update the models continuously depending on the evolution of the vehicle fleet.
- The stiffness (or force) level of a structure is controlled by two main parameters, geometry and material. The main objective of the crash relevant structures is to absorb the crash energy. Using reverse engineering the contribution of the absorbed energy can be estimated by analysing detailed vehicle models (provided by NCAC or OEMs). Taken into account the total amount of energy that needs to be absorbed (depending on the crash configuration) the stiffness of the structures can be defined. Low and high speed crashes (e.g. repair cost crashes like RCAR bumper test and Euro NCAP) provide information about strain rate dependencies of the materials.

Validation:

- Generic crash responses w.r.t different vehicle classes need to be specified analogue to the creation of generic structures average crash pulses and deformation behaviours can be used to validate the corresponding vehicle models of each vehicle class. Objective assessment tools and corresponding thresholds can ensure validated models independently from the chosen crash solver.

The database developed within FIMCAR offers a good starting point. A large number of tests provide data for baseline crash behaviours for different crash scenarios. In combination with the structure database established in VC-COMPAT, baseline topologies of the EAS can be modelled. However, to model appropriate representatives of the European fleet, more data is needed. One way to collect these data could be to monitor crash pulses and deformation behaviour as well as the topology of the structure concepts during the homologation process of future vehicles.

Other important points are modelling parameters already mentioned, like mesh size, materials, contacts and parameters ensuring numerical stability. At this time no thresholds can be defined to specify these parameters. Further research is needed to answer these open questions.

3.3 Deformable Barrier Models

Two new deformable barrier types were investigated within FIMCAR: the progressive deformable barrier (PDB) and a deformable element in front of a full-width barrier (FWDB). Compared to the test configuration used in ECE R94 and EURO NCAP, the new test configurations are intended for analysis of the partner protection potential of the tested car. In case of the PDB, the deformation pattern of the barrier is primarily used to analyse load spreading. In case of the FWDB, the deformable element is used to prevent engine dump and to activate the front structures in a more realistic way then it is done in a full-width rigid barrier test (FWRB). Furthermore, the forces applied to the wall are measured by load cells. The assessment metrics require minimum forces in specific areas of the wall in both test configurations the deformable element is crucial for the assessment of the vehicle. The main properties that influence the final deformation pattern of the PDB are the stiffness and strength of the honeycomb as well as the cladding sheet. In terms of the FWDB, the deformable element is responsible for some minor load spreading effects and therefore for the load distribution measured on the wall.

3.3.1 Today's Requirements for FE Barrier Models

In Europe, the same deformable barrier (ODB) is used in regulation and consumer tests for frontal impacts. The specification and detailed description of the barrier is given in [ECE 2010]. In addition to the geometrical data, material type and stiffness of the barrier as well as the certification process is described. This certification process requires different specimens to be extracted from the barrier for tests by dynamical loading. In this way the stiffness of the honeycomb block is validated and the barrier can be certified.

For the development of the FE barrier model, geometry, material type and (axial and shear) stiffness of the honeycombs are essentially the only requirements that are needed to be fulfilled to create a validated model. In terms of the ODB, this is sufficient due to the fact that neither the barrier deformation nor the barrier forces are analysed after the crash. Additionally, in house requirements of the provider or the OEM itself can be defined.

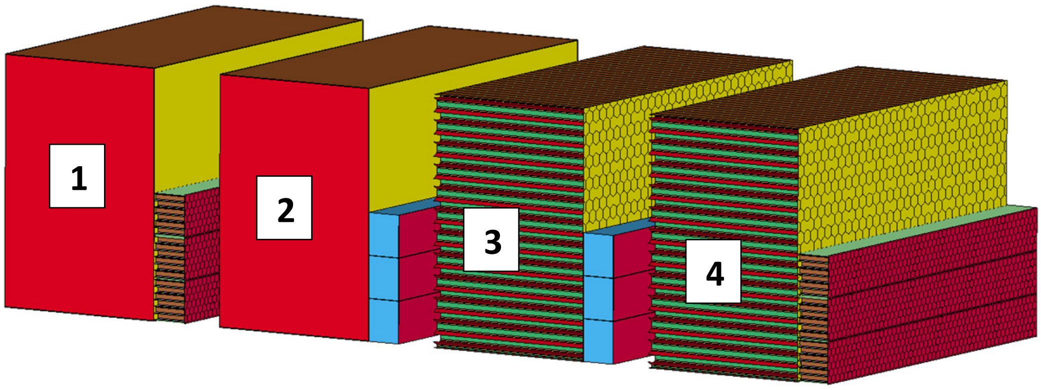

Figure 3.3: Different ODB FE barrier model designs [Bala 2003].

Table 4: Comparison of different ODB FE barrier models [Bala 2003].

Barrier Number (See *Figure 3.3*)	Main Block	Bumper Block	Number of Elements
1	Solid elements	Shell elements	193,655
2	Solid elements	Solid elements	64,119
3	Shell elements	Solid elements	380,973
4	Shell elements	Shell elements	1,504,793

Different fields of application lead to different modelling approaches to simulate the behaviour of the honeycombs. Between the trade-off of accuracy and time consumption, the user must decide which model design is the best for the intended application. Figure 3.3 shows different designs of the ODB as provided by the LS-DYNA crash solver [Bala 2003]. Depending on the design the number of elements, as one of the most important criterion in FEM simulation, increases dramatically with the level of detail. The level of detail changes dramatically when the element type changes from solid to shell elements and the complexity of the barrier model becomes the same order of magnitude as a full vehicle model. Comparisons of element model and barrier modelling are presented in papers like [Yasuk 2008].

3.3.2 Requirements for PDB model

Due to the fact that there was no commercial FEM model of the latest PDB version available, a new model was created by GME [Stein 2012] within the FIMCAR project. Within the development, the standard procedure of barrier modelling was used. The first version of the barrier showed a very good correlation of the acceleration pulse of the colliding vehicle. As described above the validation was only done with respect to geometrical requirements and material characteristics, in particular the axial loading of the honeycomb blocks. This model (PDB v1) was used for some initial runs with the PCMs. The preliminary results showed that correlation of the deformation behaviour of the barrier model with the real barrier was very poor. One of the identified problems was that the lateral stiffness of the barrier model was too soft. Thereby the honeycomb blocks moved to the left during the rotation of the vehicle around the right edge of the PDB, Figure 3.4. Another problem was the created footprint. The deformation pattern of the barrier showed no correlation with typical footprints of real cars of the corresponding vehicle class (executive car). However, due to a lack of suitable PDB metrics no objective assessment could be done. Based on the subjective assessment of the deformation behaviour and the footprint, it was decided that the quality of PDB version 1 was not sufficient for the use within FIMCAR.

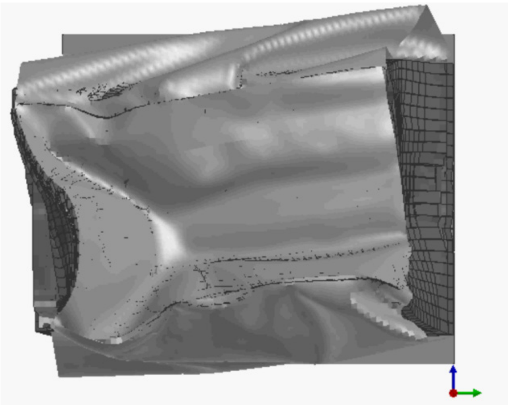

Figure 3.4: Deformation behaviour of PDB model version 1.

A second model was created (PDB v2) with respect to the identified problems. Within this validation process, the focus was the creation of realistic deformation behaviour of the honeycombs. Therefore the lateral stiffness and the rupture were fitted to test data coming from the two certification tests (trolley with rigid plate and tubes) for the barrier and finally validated with real crash test data. The following simulations show a good correlation of the barrier model in terms of deceleration pulse and deformation pattern of the barrier, Figure 3.5.

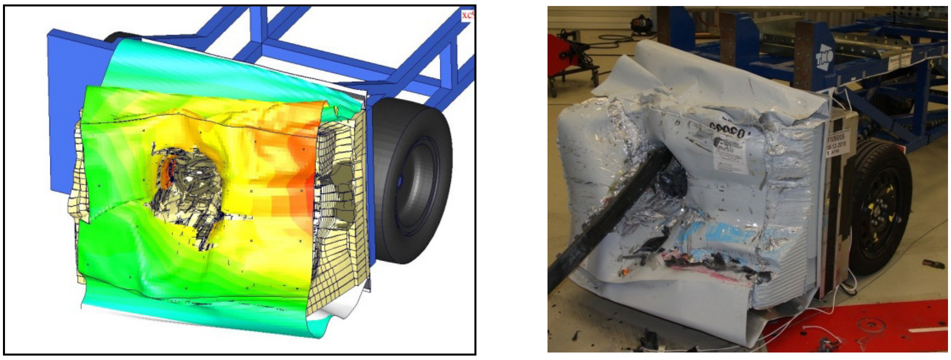

Figure 3.5: Comparison of PDB version 2 model with real crash test.

3.3.3 Summary and Conclusions

Different barrier models were used within FIMCAR. On one hand, the ODB FEM model, which is a de facto standard tool in the product development process and new barrier models like PDB and FWDB. Due to the fact, that the new deformable elements are used differently than in the past (i.e., barrier deformation pattern for PDB and force transfer through the barrier for FWDB) the model quality needs to fulfil additional requirements compared to today. These are:

- Load spreading
  - Information about lateral stiffness of honeycombs
  - Force transmission through rivets, intermediate plates or glued connections
- Rupture of material
  - Exact thresholds for material rupture needed
  - Rupture mechanisms need to be identified

Two different scenarios seem to be capable to address the requirements needed for barrier modelling:

1. Expanded certification process

A specific number of dynamic test configurations need to be specified. The tests shall load the barrier with realistic loadings (e.g. energy, structures). A specific number of thresholds need to be fulfilled addressing requirements like load spreading, deformation pattern as well as today's standard requirements.

2. Specific definitions of material characteristics

A detailed confirmation of the validated barrier model in terms of material behaviour (honeycombs and cladding/intermediate plates) and connection characteristics (glued and rivet connections) need to be provided. The final validation can be done by a specific test where either a predefined deformation pattern has to be created or a specific amount of load spreading is allowed.

Both scenarios are suitable to provide enough data for a barrier modelling process. Dynamic tests have the advantage that boundary effects like the trapped air in the honeycombs, are taken into account as well. Furthermore, realistic loads provide the benefit that the barriers behave during the certification in the same way as they do in real crash test.

The most important conclusion is that the minimum requirements for barrier models are not sufficient to create the new barrier models investigated in FIMCAR. New requirements need to be defined to ensure a realistic behaviour of any FEM barrier model.

3.4 Different Crash Solvers

Today, several commercial crash solvers are available and are used by the industry. Within FIMCAR, all FEM models should be made available for the three crash solvers (LS-DYNA, PAM Crash and RADIOSS) used by the industrial partners of the consortium. For the modelling process, a specific knowledge of the used crash solver is necessary. Basically the modelling approach is the same, but particular numerical effects (e.g. hourglass and shear lock effect, mass adding) require solver specific controls to handle the effects and to ensure stable calculation and valid results. Furthermore, there are no commercial tools available which can reliably "translate" models from one solver into another. The geometrical definitions such as the translation of nodes, elements and the corresponding parts do not cause problems. Definitions of more software specific parameters for materials, contacts, constraints and loads are problematic however. The treatment of kinematic options also differs between the solvers. These entities have to be defined manually and is very time consuming and prone to errors. Another problem that has an influence on the results is the computer and its hardware components. Solving the FEM generated numerical algorithms depends on the interaction of the hardware components. Especially the last point is influenced by multi CPU clusters. The following three main parameters are responsible for the quality of the results of different solver:

- Knowledge of solver dependent controls to handle numerical effects
- Knowledge of solver specific definitions to set up model characteristics
- Influence of hardware used for the calculation

Within the modelling process, all of these three main parameters were taken into account. Within FIMCAR, no thresholds were defined for the validation of the models for the different crash solver, Figure 3.6. The comparison of the results was made subjectively according to a standard validation process (real world – model) and engineering judgment. The following section deals with the possibility of objective assessment of crash solver responses.

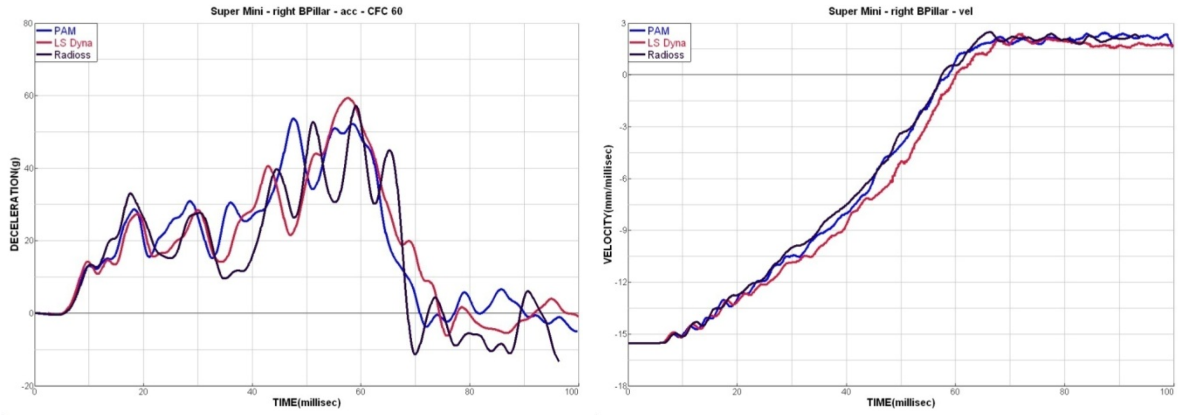

Figure 3.6: Comparison of crash solver responses (PCM Super Mini; left side – deceleration; right side velocity).

3.5 Objective Response Assessment

The growing role of FEM simulations in the product development process requires tools for the objective assessment of measurements in particular for the validation process of FEM models. Different approaches are available to compare signals against each other:

- Comparison of specific values of a signal (e.g. maximum peak at specific time)
- Comparison of curve characteristics in a predefined interval

While the comparison of specific values is less difficult, the assessment of the correlation of the whole curve with the original one is very complex. Several possibilities exist that were used in different fields of applications (e.g. curve fitting, signal analysis) to make an objective assessment of two curves. The following list gives an overview about commonly used methods:

- Corridor methods
- Cross correlation method
- Least square method

3.5.1 Corridor Method

This method uses corridors to assess the correlation of two curves, Figure 3.7. Different rating levels can be used to weight the distance between the curves [Gehre 2009]. At least one corridor needs to be specified. The width of the corridor can be set up to different values (e.g. +/- root mean square deviation, +/- x-% of average of each point or of the maximum peak value, user defined values).

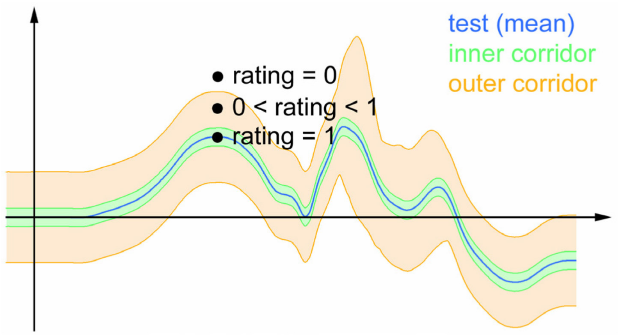

Figure 3.7: Corridor method with two corridors using three rating values [Gehre 2009].

3.5.2 Cross Correlation Method

Basically this method is used in fields of signal analysis. Separate analyses can be made and independently compared against each other: phase shift (see Figure 3.8), size of area under the curve and shape of the curve.

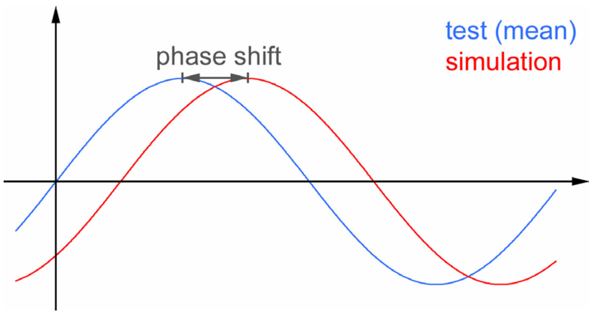

Figure 3.8: Example for cross correlation – phase shift [Gehre 2009].

3.5.3 Least Square Method

Optimisation tools commonly use this method for curve fitting optimisation. The goal of this method is to minimise the sum of the residual difference between an objective curve and the original curve. As well as values calculated by corridor and cross correlation method, the sum of the residuals can be used as an indicator of the correlation of two curves.

Many individuals and organisations have developed software to perform the comparisons of different curves. The NCHRP 22-24 [Ray 2010] project developed a Matlab[1] based script that uses a variety of metrics to compare curves with the specific application to road restraint systems.

3.5.4 Summary

The objective assessment of curves e.g. within the validation process of FEM models can help to improve the model quality and can reduce the effort needed for the validation. Furthermore these tools offer the potential to compare different crash solver against each other. Special models addressing numerical effects and their treatment by the solver can be used to adjust the solver settings. Objective curve assessment can provide thresholds that need to be fulfilled before the settings can be used in the final model. In that way, it is possible to exclude the influence of the solver from the model response. As already mentioned, the identification of appropriate thresholds is crucial before the objective assessment can be applied.

[1] Matlab is a product of The MathWorks (www.mathworks.com)

3.6 Model Verification and Validation

The general flowchart elaborated within IMVITER (Figure 3.9) evolved the flow chart of Regulation 371/2010 into a clearer version based on 3 phases: model verification, model validation and type approval [Eggers 2012].

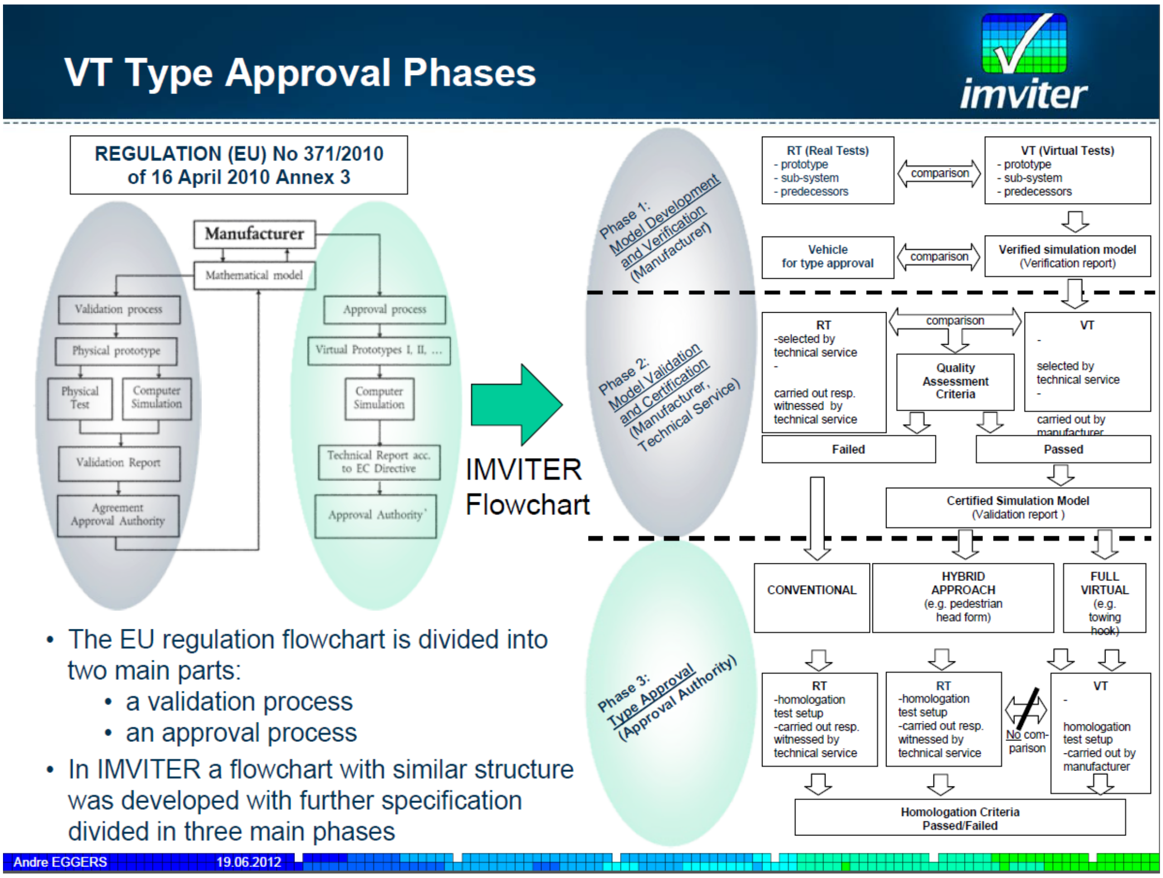

Figure 3.9: Type Approval Phases according to [Eggers 2012].

The type approval phase can follow 3 approaches (in addition to the conventional case with real testing only):

Full VT: Type approval technical requirements are assessed only with VT.

Hybrid VT: Type approval technical requirements are assessed with a combination of physical test and VT.

Extension of Approval (EoA) based on VT: A vehicle is type approved based on simulation predictions obtained from a model, which is obtained from a predecessor model previously validated, and with small modifications.

The numerical model is validated in Phase 2 against real testing results: the model is accepted when the proper validation criteria (metrics, with threshold values depending on the specific application) are satisfied (then ensuring an adequate level of overlap between numerical and virtual outputs, for the specific test set-up/configuration concerned).

All the phases described in the detailed procedures or flowchart have to be summarised at the end within reports that have to be approved by the Technical Service. These reports need to include a minimum amount of information in order to prove the verification and validation of the involved models (phase 1 and phase 2 of the general IMVITER flow-chart respectively), so that they can be accepted and used for the Type approval (phase 3). In practice, the model verification report is used for the identification of the model, i.e. proving that the virtual product/tool actually represents the real one. The model validation report describes the model ability to reproduce the reality, i.e. assesses the predictability of calculation results. In this report, the results of simulation runs are compared to the ones from the reference experimental test and judged according to the selected metrics/validation criteria. For each presented calculation, a check of the loading conditions (set-up) and of the numerical correctness (e.g. energy balance, added mass, etc.) associated to the corresponding run also has to be passed and this is called verification of the run. So the model validation report always provides the evidence about verification of calculations and validation of their results. The general reporting approach defined within IMVITER is summarised in Figure 3.10 [Puppini 2012]

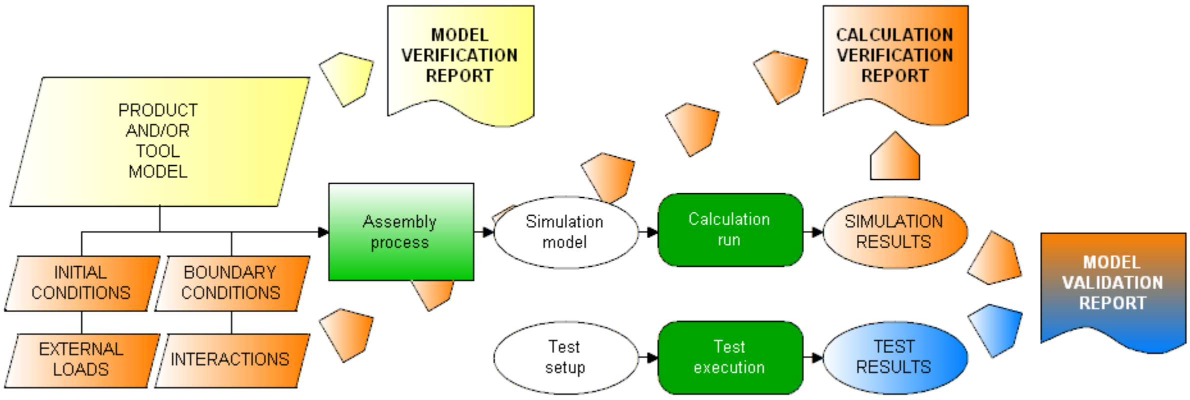

Figure 3.10: Reporting approach according to IMVITER [Puppini 2012].

IMVITER delivered report templates for the pilot cases that were studied and these represent the main synthesis of the virtual testing procedures and a basic reference for each future implementation of VT in regulations.

Several metrics were suggested in the past and are then available for the objective comparison of results required by the model validation phase. Some of them were preliminarily proposed in IMVITER (together with the threshold values for the pilot case concerned) for the validation of the model results and then included within validation report templates.

ISO-TC22-SC10-WG4 on Virtual Testing is currently active on the elaboration of an ISO standard for the objective comparison of two signals. The release of such a reference standard on metrics will probably lead to an update of the criteria preliminarily proposed in IMVITER for its pilot cases, other than creating a new basis for criteria considered in future VT regulation developments.

Pedestrian protection is currently not included among the regulatory acts in which the use of virtual testing is allowed. An in depth study on this specific pilot case was performed within IMVITER and the corresponding results will form the basis for future evolution/refinements of the current Regulation.

Euro NCAP rating has introduced the possibility to use numerical simulation results within the pedestrian protection evaluation “box”. This option is already considered within the forthcoming new Pedestrian protection Protocol (version 6.0 from February 2012) for the assessment of vehicles with active bonnets, where the numerical simulations, involving standing pedestrian models of different sizes, will be required to identify the ‘hardest to detect' pedestrian and support the choice of test tool. The simulations will concern the pedestrian statures that result in head contact with the bonnet and acceptable numerical models and codes are specified in a dedicated Appendix.

For the evaluation of the head-to-bonnet impacts according to the so called Grid Method, the OEM is required to provide Euro NCAP Secretariat with HIC or corresponding colour data detailing the protection offered by the vehicle at all grid locations on the bonnet (defined through an appropriate geometrical procedure). These predicted values or colours can be the results of numerical simulations and shall be provided before any test preparation begins. The predicted level of protection offered by the vehicle is verified by Euro NCAP by means of testing of a sample of randomly selected grid-points and the overall prediction is corrected accordingly, i.e. through the application of a correction factor generated by comparing the outcome from the randomly selected test locations with the predicted results supplied in advance for the same points. Only data that results in a correction factor between 0.500 and 1.500 are accepted and where this is the case, the headform score will be based on the predicted data score with the correction applied.

The Grid Method represents a first practical application/implementation (with additional elaborations) of the possible virtual testing approaches proposed within APROSYS (overall map of predicted VT results generated in advance on a series of points evenly distributed within the impact areas of the vehicle and made available) and presented in occasion of its Final Event [Puppini 2009].

4 FRONTAL COMPATIBILITY EVALUATION

4.1 Introduction

Numerical (FE) simulation is a reliable tool for the assessment and optimisation of car design and facilitates reduced testing efforts. Each OEM largely relies on this tool during its product development process. For this reason, only with simulation tools a realistic and wide coverage of car-to-car compatibility issues (w.r.t. the real accident situations that may happen on the road) can be reached with acceptable/sustainable costs. Real car-to-car tests are very expensive and only provide information at specific sensor locations or areas observed in film coverage. For this reason, car-to-car compatibility was identified as one of the fields with higher potential towards VT applications, with benefits in terms of enhanced real world safety [Puppini 2009].

Numerical simulation offers a resource to address the complexity introduced with new frontal impact requirements as well as offers extended evaluation of compatibility beyond the physical tests. The remainder of this chapter discusses the types of possible simulations to assess compatibility and the technical challenges for their implementation. In the following, VT is defined as the use of numerical simulation models to reproduce real tests for regulatory purposes, according to the definition given within IMVITER project [Cordero 2012]. While not all numerical simulation activities are VT, e.g. the ones like model development and its internal use for design purposes, VT can be considered as the common area between numerical simulation and legislation. The latter can also represent more general standards like internal industry or those used as a reference for voluntary agreements and/or ratings. In other words, only numerical models that pass appropriate and agreed verification and validation procedures and are then certified by regulatory bodies (through their Technical Services) can be used for VT (where the results of the numerical simulations performed with such certified models are used for assessing the compliance with regulatory prescription/requirements).

4.2 Implementation Options

Compatibility is an issue exceeding the borders of the vehicle fleet of one manufacturer, as real car-to-car impacts occurring in the entire vehicle fleet. Confidentiality and use of different software codes make it impossible to simulate crashes between car models of different OEMs. Due to this important limitation, for an OEM the only practical way to proceed to evaluate its products' performance is to use a virtual common target vehicle – or better a number of common target vehicles – that is not restricted by confidentiality or commercial interest.

Within FIMCAR this way was addressed through the generation and use of Generic Car Models (GCMs) and Parametric Car Models. The concept of GCMs was born and already successfully applied within the past APROSYS project but a second generation of these models was specifically developed for the use towards frontal impact compatibility issue.

In general, when examining the use of virtual testing tools for compatibility aspects, typically full car crash simulations are considered, that can be classified w.r.t. the different type of impact configurations (numerical set-up) involved:

a) Specific vehicle-to-barrier(s)
b) Specific vehicle-to-itself (car-to-car)
c) Specific vehicle-to-other specific vehicle of different class (same OEM)
d) Specific vehicle-to-common/standardised reference vehicle of same class (GCM approach)
e) Specific vehicle-to-common/standardised reference vehicle of different class (GCM approach)

Again in general, simulation tools or Virtual Testing for compatibility evaluation can be seen under 3 different macro-perspectives/scenarios:

1) For vehicle design/development purposes
2) For "interim" regulatory purposes (compliance to voluntary agreements and/or ratings)
3) For regulatory purposes (vehicle type approval)

Vehicle design/development is nowadays largely based on simulation tools and the inclusion of compatibility aspects is not posing particular operational problems. Impact configurations of type a) are normally considered within the virtual activities supporting the product design & development phases during the standard product development process (PDP) adopted by OEMs. Configurations of type b) and c) are also considered/explored by OEMs but only for specific verifications of the vehicle overall crash behaviour and/or research purposes and not an integrated part of the systematic design approach. Current industrial crash simulation procedures/practices are ready to deal with typical compatibility aspects and scenario 1) is the one with the short term applicability. Configurations of type d) and e) are feasible also within this scenario, provided that representative generic car models are made available and agreed/recognised within the industry as the reference tool for this type of crash simulation based compatibility analyses.

The second scenario ("interim" regulatory purposes), can be seen as an extension of current industrial procedures/practices for full car crash simulation but on a voluntary agreement basis and/or on requests coming from new rating protocols. The time frame for this could be the medium term perspective. The definition of a VT standard focused on compatibility needs an appropriate period of discussion for convergence towards a procedure that is agreed within appropriate TWGs (Technical Working Groups), and then to be applied on a voluntary basis by OEMs or within a rating protocol. This voluntary (or independent, in case of ratings) characteristic is the factor that could speed up the development of such a VT standard w.r.t. a classical regulatory act. This scenario could involve obviously all the previously mentioned crash configurations, from a) to e).

The third scenario, i.e. VT within the regulatory purposes, requires the OEM to strictly follow predefined procedures to ensure that the models adopted to produce the results are adequately predictive. This means that the virtual models are verified and validated against real results, through the use of appropriate correlation criteria/standards (introduced in Chapter 3). It has already been highlighted that such types of approaches have been/are studied in dedicated international projects/working groups (i.e. IMVITER, ISO WG4). The complexity levels considered to date, however, are still far from the full car crash configuration necessary for frontal impacts, so the scenario 3) appears to be the most difficult to be implemented. The most complex type approval procedures considered within the IMVITER project were pedestrian head and leg form impacts where no complex material behaviour (local and global buckling, material failure, etc.) are significant in the dynamic event.

Full car FE structural analysis is widely applied within industry but testing is still essential for the manufacturers to have confidence in the product's performance. Better damage and rupture modelling is needed for predictive structural analysis. Component tests help to validate models locally but an experimental full system response may still disclose unexpected failure modes in different scenarios. Therefore VT for type approval applications vs. compatibility aspects seems to be still a very complex case, even for the classic crash configuration of type a). For these reasons, scenario 3) is seen as a more long term perspective where all the crash configurations (a) to e) can be involved.

The previously discussed classifications and contents can be organised in a matrix in order to visually identify the level of potential application. Colour coding is used to show the difficulty of the issues.

In Table 5, the situation described in the previous paragraphs is presented using the following colour code: green=currently feasible/short term perspective; yellow=medium term perspective; orange=long term perspective).

Table 5: Matrix showing the level of potential application of VT for compatibility purposes.

		Scenarios		
		1) For vehicle design /development purposes	2) For "interim" regulatory purposes (compliance to voluntary agreements and/or ratings)	3) For regulatory purposes (vehicle type approval)
Numerical test set-up	a) Specific vehicle-to-barrier(s)		X	
	b) Specific vehicle-to-itself (car-to-car)		X	
	c) Specific vehicle-to-other specific vehicle of different class (same OEM)			
	d) Specific vehicle-to-common/standardised reference vehicle of same class (GCM approach)		X	
	e) Specific vehicle-to-common/standardised reference vehicle of different class (GCM approach)			

The last two cells of scenario 1) column are indicated in yellow because the availability of agreed/recognised representative generic car models as reference tool still needs some additional steps forwards, w.r.t. GCMs used within FIMCAR. Moreover Scenario 1) is related to common/normal industrial internal activity performed by OEMs within their PDPs, as already mentioned. In this case, the discussion of VT potential for compatibility assessment has not been addressed to date. This document is not focused on this scenario but rather on the other two as defined in the beginning of this chapter.

According to this and to the experience done with VT applications in FIMCAR, the area (cells) of the matrix indicated with an "X" are then the ones on which the following considerations are mainly based.

Scenario 2) involves, other than a target car model (specific real vehicles but even GCMs/PCMs), the model of the specific barrier type concerned (FWRB, FWDB, (M)PDB, ODB): in view of VT application, the models of tool concerned need to be verified and validated, too, according to common procedures/templates that need to be defined and agreed. Within FIMCAR different barrier models were used in certain configuration simulations (FWDB and PDB) by different partners, even if the level of equivalence between them were not assessed against a common validation and verification procedure (V&V). A preliminary V&V certification of this type will be required in the future. It is believed that this procedure can be defined and agreed within a relatively short time window (i.e. compatible with the medium term perspective), as barrier model verification and validation process is already today done at different sites according to similar procedures and only aspects like common reference experimental results and correlation criteria/metrics for the model acceptance need to be shared and formalised.

Scenario 2 is an area where the numerical simulation can support the selection of "worst case". In the FIMCAR-proposed compatibility approach two load cases should be tested, both Full Width Deformable Barrier (FWDB) and Offset Deformable Barrier (ODB). The main objectives for the FWDB test are a compatibility metric and high cabin acceleration driven dummy criteria. The car configuration that represents the worst case for the FWDB metric could be the smallest powertrain version (the powertrain that loads the deformable barrier latest in a FWDB test), and the option level that gives the lowest curb weight. This may not be the same configuration that produces the worst case for dummy loading as the dummies may have a longer ride down distance. For the ODB test, the objectives are to test structural integrity and intrusion driven dummy criteria. The worst case car configuration should be the powertrain version and option level that creates the highest intrusions in the driver compartment area.

Internal discussions within the FIMCAR consortium have resulted in the decision to identify a worst case vehicle configuration for the FWDB and ODB test separately. Thus, crash simulation can be used to demonstrate the worst case vehicle configuration prior to the homologation testing to be approved by a technical service. Crash simulation can thereby supplement the test data if the vehicle and barrier models can be verified and validated through acceptable procedures.

FIMCAR adopted the concept of GCMs by developing new improved versions and using them extensively in the numerical simulation activities involving the car-to-car crash configurations (numerical set-up a), b) and d)). The approach followed in this activity already contains all the main elements that a future V&V procedure for certified common opponent vehicle models should implement/formalise. The GCM development process was driven by the following requirements:

- To represent typical vehicles of the actual European vehicle fleet, in terms of mass and dimensions

- To evaluate the occupant severity level through appropriate readings of the vehicle crash pulse (no restraint system and dummy models on board of GCMs/PCMs) => OLC (Occupant Load Criterion)
- To be available in all codes used by FIMCAR OEMs (LS-DYNA, RADIOSS, PAM-Crash)
- To ensure numerical stability (stable time steps, energy conservation and added masses) in all the main crash configurations considered
- Capable to interact with OEM detailed models, i.e. that can be easily included inside virtual car-to-car test set up involving a real car model as opponent
- High level of detail, similar to the one of detailed OEM models (around 600,000 to 700,000 elements each), i.e. fine mesh, especially for what concerns the vehicle front structure and all relevant under bonnet lay-out components implemented
- Realistic crash behaviour during the collision types considered, i.e. adequate deformation of the front-end structures with correct interaction of the under bonnet lay-out components, contained occupant compartment intrusion levels and realistic vehicle crash pulses
- To have main rails with an adequate overlap w.r.t. the “part 581 common interaction zone”
- To be properly instrumented, in order to permit the monitoring of relevant structural parameters/indicators
- Validation towards the achievement of a good overlap with real US NCAP pulses (“realistic” behaviour) and equivalent model responses among the different codes (LS-DYNA, RADIOSS and PAM-Crash)

The formalisation of the way to obtain such certified virtual common reference car models and the corresponding availability of these first generation of reference tools, agreed/recognised on a wider scale, seems to be feasible in the medium term as demonstrated by the successful application of GCMs in the FIMCAR project. The FIMCAR applications even take into account further evolution of GCMs simulation output and metrics to judge their level of realistic behaviour or representativeness (e.g. average values of public available crash pulses as reference curves for objective metric applications, corridors derived from the specific class real curve envelopes, etc.). There is also a great potential w.r.t. harmonisation, as this type of approach (availability of common opponent models) is something considered also outside EU. The In the US a fleet of FE models was developed by NCAC that represents a similar way to provide common opponents for VT. The main difference between the US and EU approach was that the NCAC models are reverse engineered models of available car models while GCMs are virtual car models with no physical counterpart. Both approaches can coexist in the future and be integrated with each other. Past car crash compatibility studies in the US have seen a relevant use of NCAC models to complement the real car-to-car crash test programs [Patel 2009, Stein 2013/1, Park 2009].

Any reference generic models family, once adopted as a tool for VT based evaluations, has to be updated periodically in order to reflect the fleet evolution. This is undoubtedly a huge task (models architectures, code versions etc.), with associated costs and efforts that can be probably managed only by dedicated institutions and/or accredited companies having this by mandate and/or core business.

An important step forward can be the convergence/integration of the two approaches used within FIMCAR, i.e. GCMs and PCMs. Detailed GCMs can be based on a parametric CAD geometry (like PCMs), permitting relatively fast changes of architecture and/or ”jumps” between adjacent classes, other than an easier updatability (in order to take into account fleet evolutions), while maintaining an high level of detail in the models. This evolutionary step is called PGCMs.

The number of reference models (vehicle classes represented) cannot become extensive in order to maintain feasible dimensions for the simulation run matrix required for VT evaluation of car-to-car configurations. A manageable/sustainable range could be 4 classes: Supermini, Small Family, Large/Executive, and SUV. For this reason, the number of car-to-car crash configurations to be considered in a procedure has to be limited to a minimum (e.g. one closing speed, two horizontal, and two vertical offsets).

5 DISCUSSION

Several road maps considering the introduction of VT in regulations have been presented in the past decade: Advanced Passive Safety Network (APSN) in 2004 and 2006, CARS21 in 2005, IRCOBI in 2006 and APROSYS in 2009 [Puppini 2009]. All of them dealt with the general aspects summarised in the following list, even if with some differences in the type of approach and/or focus (e.g. more emphasis on expected time for certain VT phases introduction/implementation than on their details or vice-versa):

- Development of standardised model validation procedures and tools
- Evaluation of model/simulation quality/predictability
- VT acceptance as assessment method in regulations
- Expansion of regulatory test configurations with VT
- Implementation in regulation/ratings (first on simpler cases and then on more complex ones, with integrated approaches)
- New advanced VT tools (dummy and especially human body models, with improved injury criteria and potential to cover a much wider range of occupants, in terms of size, age and gender)

In the following section, however, the IMVITER Roadmap for VT implementation is introduced and reviewed.

This is the latest roadmap that was released (June 2012) by a research project that ran in parallel with FIMCAR and that made a significant step forward on the subject. Considerations about the specific case of VT vs. compatibility aspects will be then made on the basis of this up-to-date document [Seibert 2012].

Figure 5.1 shows the roadmap presented at the IMVITER Final Meeting (19th June 2012). As it can be seen from the figure, it is expected that Real Testing (RT) and Virtual Testing (VT) will coexist in the future but, from 2018-2020 on, a growth in the proportion of VT in regulation is foreseen. An increasing and relevant presence of full VT based type approvals is predicted from 2030 onwards.

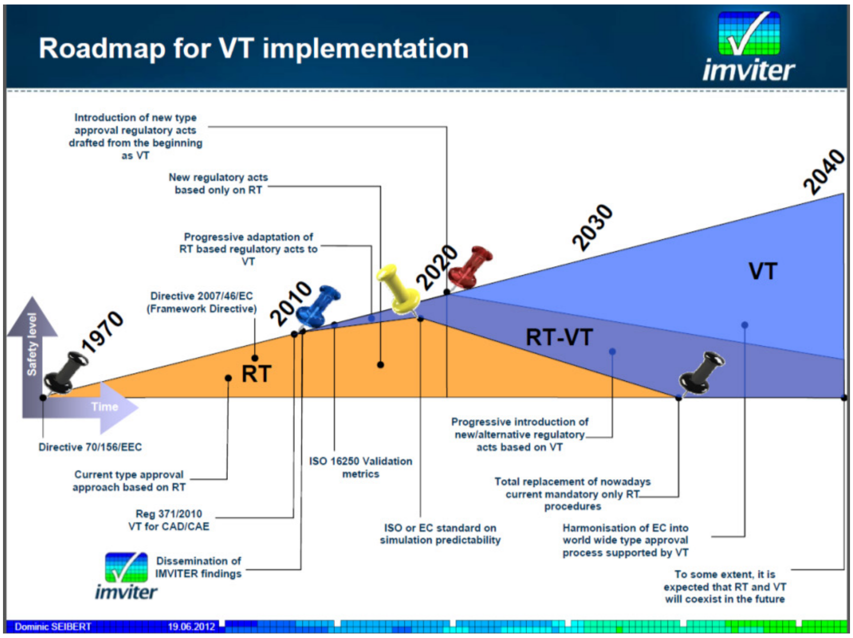

Figure 5.1: IMVITER roadmap for VT implementation [Seibert 2012].

The use of VT towards compatibility aspects can be positioned within this roadmap. A time frame for integrating VT into full vehicle VT is presented below with the potential for full certification by simulation identified.

Step 1

2013-2020: further evolution of GCMs concept and consequent availability of first agreed/recognised reference VT model family for regulatory/rating application, with associated definition of verification and validation procedures/templates. Convergence towards PGCMs concept for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models and then also capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020-2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly (i.e. through indicators like OLC or other similar criteria) as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted to type approve model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025-2030: first full vehicle-crash regulations (vs. type approval and even self-certification) for car-to-car compatibility based fully on VT (structural behaviour and dummy biomechanical response on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030-2040 Type approval based on full system simulations (structural and biomechanical behaviour included, with HBMs as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the prescriptions).

The above mentioned four steps for VT implementation vs. compatibility aspects, obviously, have to face some obstacles/difficulties: the main ones are indicated in the following Table 6 and Table 7.

Table 6: VT implementation steps & obstacles.

Roadmap step	Description	Obstacles	Possible solutions
*Step 1: **2013-2020***	*Specification of vehicle model requirements for use in type approval support actions (i.e. worst case selection)-Further evolution of GCMs concept: PGCMs equipped with generic restraint systems and occupant models* *- First agreed/recognised reference VT models family for regulatory/rating application* *- Convergence on the dimensions/typology of the simulation run matrix required for VT based evaluation of car-to-car configurations*	*-Agreements between industry and rulemaking bodies on model properties and criteria that are not design restrictive* *-huge and then expensive task (different models architectures, different code versions, etc.)* *- need of periodical update of VT models reference fleet, according to evolutions in real fleet and in numerical simulation techniques state of the art (SotA)* *- long process to obtain agreement on common VT tools and procedures*	*- dedicated public funded projects* *- dedicated institutions and/or accredited companies having the PGCMs maintenance as mandate and/or core business* *- activation of specific international technical working groups elaborating the VT procedures and reaching the necessary agreement*
*Step 2: **2020-2025***	*- first ratings and/or voluntary agreements for compatibility purposes, including car-to-PGCMs virtual crash configurations* *- main focus on vehicles structural behaviour* *- occupant behaviour: indirect evaluation through indexes (like OLC) as minimum requirement; available option for direct evaluation through occupant models*	*- difficulties/delays in completing the previous Step 1* *- complexity of VT procedure, i.e. complex models, complex templates to report all results, high amount of CPU time needed to perform the required simulation matrixes*	*- keep complexity level under control, by focusing on procedures/requirements sounded with the SotA of the period* *- automation of the procedures (integration within Product Data Management Systems)* *- continuously improving performances within HPC field (High Performance Computing)*

Table 7: VT implementation steps & obstacles (continued).

Roadmap step	Description	Obstacles	Possible solutions
Step 3: ***2025-2030***	*- first full vehicle-crash regulations (type approval /self - certification) for car-to-car compatibility based on fully on VT* *- structural behaviour and at least dummy biomechanical response on PGCMs*	*- difficulties/delays registered in previous step 2* *- differences in VT procedures for different regulatory approaches (type approval and self-certification) in different areas of the World*	*- harmonization of VT procedures (within the overall process of harmonisation of type approval procedures and world- wide regulations*
Step 4: ***2030-2040***	*- type approval based on full system simulations* *- structural and biomechanical behaviour included* *- HBMs as occupants of specific car and PGCM opponents* *- enhanced injury criteria in the prescriptions*	*-possible relevant changes in the real fleet mix, with the presence of new vehicle concepts (e.g. Full Electric Vehicles) becoming comparable/ predominant w.r.t. traditional cars, with associated changes in the overall compatibility picture/problem and needed safety countermeasures*	*- more lean and flexible rule/regulation making processes (update/extension of existing procedures)* *- timely generation of new PGCMs providing appropriate reference models for the new vehicle classes (e.g. REVMs, Reference Electric Vehicle Models)* *- integration of Active-Preventive safety systems effects within VT procedures*

6 SUMMARY

The objective of this deliverable was to analyse the potential of simulation tools towards the evaluation of compatibility. A historical recap and a review of the on-going activities to implement simulation tools in automotive type approval and rating processes was performed. Extensive work is on-going in Europe within this subject. The EC founded IMVITER project aimed to help and support in the definition of upcoming virtual type approval procedures. The outcome from IMVITER combined with the experience from the use of simulations tools in FIMCAR was used as a base for the analyses and discussions on how to implement compatibility in the virtual type approval processes.

A roadmap with a 20-30 years perspective is proposed with the evolutionary steps towards a type approval based on complete system simulations, including both structural and biomechanical evaluation. The obstacles and their possible solutions are discussed for each step. However, obstacles still remain to be solved before a complete type approval can be possible, but the use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

7 GLOSSARY

ams	auto motor und sport (German automotive magazine)
EAS	Energy Absorbing Structure
FE	Finite Element
FWDB	Full Width Deformable Barrier
FWRB	Full Width Rigid Barrier
GCM	Generic Car Models
HBM	Human Body Model
HPC	High Performance Computing
NCAC	(US) National Crash Analysis Centre at George Washington University
ODB	Offset Deformable Barrier
OLC	Occupant Load Criterion
PCM	Parametric Car Models
PDB	Progressive Deformable Barrier
PDP	Product Development Process
PEAS	Primary Energy Absorbing Structure
PGCM	Parametric Generic Car Models
REVM	Reference Electric Vehicle Model
SEAS	Secondary Energy Absorbing Structure
SotA	State of the Art
TCMV	Technical Committee – Motor Vehicles
V&V	Verification and Validation
VT	Virtual testing

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FIMCAR
XV – Fleet Studies

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

Subject of this study is the development of a generic method to evaluate the characteristics of future vehicle fleets, which assist in vehicle compatibility research. The ever increasing demands for occupant safety have led to improved crashworthiness of vehicles. However, vehicles have become increasingly stiff over the last decades. In combination with a trend of heavier and higher vehicles this results in more aggressive and incompatible vehicles. Also the trend of smaller and lighter vehicles results in a mismatch of vehicles. Compatibility research focuses on improvement of crashworthiness while taking the safety of a possible crash partner into account with the aim to reduce the injury risks off all crash partners. In this regard it is important to conduct research of behaviour on a fleet wide basis.

The generic vehicle modelling procedure developed in FIMCAR was used to generate a set of MADYMO models of various vehicles. Due to the limited available data, only three different car models could be made, the Supermini 2, Small Family Car 2 and SUV 4. The created models are tuned with the test data of Full Width Rigid Barrier (FWRB) and checked with test data of Offset Deformable Barrier (ODB) tests. To compensate the limited amount of vehicles additional simulations were ran with variable masses. The available models are used to run two large sets of simulations with various vehicle parameters, like longitudinal stiffness, overlap and speed. These simulations are used to evaluate the performance of the vehicle fleet. For crash severity evaluations the Vehicle Pulse Index (VPI) is used, in which higher VPI values represent a lower crash performance with higher risk of injury.

From the performed fleet studies it can be concluded that:

- A higher vehicle mass results in a lower VPI. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.
- An impact with a vehicle that shows cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle.
- A higher longitudinal stiffness results in a higher VPI, for as well vehicle 1 with stiffer longitudinal and even more for the opponent vehicle 2.

It should be taken into account that due to the assumptions made in the used MADYMO models some phenomena are not represented that might have an effect on the occupant. Cross beam failure and/or lower longitudinal stiffness result in a vehicle with lower crash stiffness in frontal impacts. This lower stiffness gives a lower VPI value, but in reality it might result in intrusion of the occupant compartment which was not taken into account in the current vehicle models.

The results of the performed fleet studies show that it is possible to evaluate and predict the effect of various vehicle characteristics on the overall crash performance of the (future) vehicle fleet.

1 INTRODUCTION

1.1 FIMCAR Project

For the assessment of real life vehicle safety in frontal collisions the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches are the most promising candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken so far. In addition another procedure (tests with a moving deformable barrier) is getting more and more into the focus of today's research programmes.

Within this project different off-set, full overlap and moving deformable barrier (MDB) test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages (WP). WP1 (Accident and Cost Benefit Analysis) and WP5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with actual car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

This deliverable describes a methodology for predicting future vehicle fleet characteristics. This based on performing various vehicle fleet studies with MADYMO models, in which a series of vehicle parameters were varied to evaluate the effect on crash severity. The MADYMO models were created with the generic vehicle modelling procedure created in FIMCAR.

1.3 Structure of this Deliverable

The deliverable starts with an introduction. The general model creation process is explained in Chapter 2. In Chapter 3 the creation of the used MAYDMO models used in the fleet studies is explained. Chapter 4 describes the actual fleet creation and evaluation of the results. In the last chapter a conclusion is presented.

2 VEHICLE MODEL CREATION PROCESS

The multi-body vehicle models shall help to perform several sensitivity analyses or investigate car-to-car crash behaviour. Furthermore, they will help to predict the effects of the desired changes in the future fleet. Within FIMCAR two other types of numerical car models are developed, the PCMs (*Parametric Car Models*) and the GCMs (*Generic Car Models*). These models are described in [Stein 2013]. However, these models are often case specific by their level of detail. A wider range of vehicle models is desired in order to research these compatibility determining factors, which will be possible by the generic vehicle modelling procedure.

This generic vehicle modelling procedure is used as a basis for designing different multi-body vehicle models in order to establish a vehicle fleet. The requirements for the vehicle models result from shortcomings of traditional vehicle models (like the PCMs and GCMs). This means computing time has to be as low as several minutes on a normal personal computer. A balance between accuracy and availability has to be found in order to guarantee reliability in combination with efficiency. Besides that, less complex models enable quick modifications on the structure of the vehicles. Prerequisite is that the vehicles need to be detailed enough to reflect the influence of distinct structural elements. In addition to that, development and validation of the vehicle models has to be done without additional real live testing.

Years of experience with multi-body vehicle models lead to the opinion at TNO that multi-body models with a simplified structure have potential for fleet wide compatibility research. Simplified models have a more stable behaviour and reduced CPU time. Based on these findings the generic vehicle modelling procedure uses the MADYMO multi-body package.

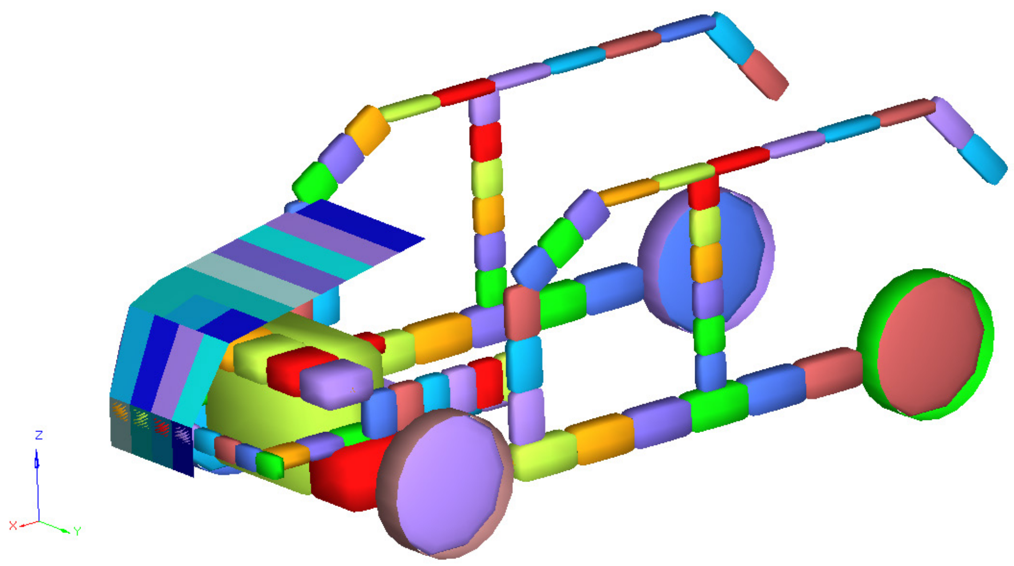

Figure 2.1: Multi-body vehicle model.

2.1 Basic Geometry

Existing MADYMO vehicle models were analysed to determine the main structural components of influence on the crash behaviour. The models were investigated to see where major deformations occur and to check if parts could be simplified to reduce computation time. The effectiveness of energy absorbing features was analysed by determination of the contribution of structures in energy transfer and dissipation. These studies resulted in a set of structural parts that are essential in a generic vehicle model.

It was concluded that the longitudinals, the shotguns, the bumper beam and the subframe suffer from large deformations. Analysis of the crush modes of these parts is essential for a correct choice of joints with optimal computing times. The longitudinals, the shotguns, the subframe and the bumper beam are also the major parts involved in energy management with regard to energy absorption, together with the engine and the wheels with regard to energy transfer. This means these parts are essential in a vehicle crash model.

In order to study frontal compatibility with the multi-body vehicle models it is important to have a realistic structural interaction and frontal stiffness. Realistic frontal stiffness is achieved by fitting the crash pulse to a real-life crash test. This is discussed separately in Chapter 2.3. Taking structural interaction into account, the geometries of the parts and their locations are of major importance. A geometrical database is used as a basis for the generic vehicle modelling procedure to obtain the geometrical data of the structural elements that have been identified as necessary for the crash models.

The part geometries can be obtained by completely disassemble the vehicle for measurements or through a numerical model supplied by an OEM. The French organisation for automotive and industrial testing, UTAC, started to set up a database with vehicle structural part measurements to facilitate compatibility research as a part of the VC-COMPAT project [Edwards 2007] . This database is used as a basis for a collection tool for the relevant data to construct the multi-body vehicle models. This collection tool can then be send to an OEM for filling in. The collection tool contains besides measurement data for wheelbase, vehicle mass, centre of gravity and H-point (for future dummy simulations) also detailed geometrical measurements for the longitudinals, shotguns, firewall, bumper and subframe. A complete set of measurement data for the frontal structure is included, together with a limited set of data for the side structure.

2.2 Model Geometry Generation

The measurement data from the geometrical collection tool are used to construct the geometries of structural elements for the MADYMO model. MATLAB is to process the measurements and to generate vehicle geometries automatically with the use of a script. The script converts all the measurement data to joint positions in the global coordinate system in a generic existing template xml file. For every body the body COG is calculated, followed by the joint position and the orientation of the joint leading to a local coordinate system. The angles are calculated with the joint positions in the global coordinate system. The size and location of the ellipsoids is determined together with the body masses and inertias. The mass and inertia of the ellipsoids are based on their size and the density of steel assuming tubular components with a defined wall thickness. However, for some parts such as engine and transmission, the mass is specified using vehicle specifications. The mass, COG and moments of inertia of the rear part (modelled as being undeformable) of the vehicle are computed to obtain the correct total vehicle mass properties. An initial stiffness function input for the structural parts is obtained from a similar situation in an existing multi-body vehicle model. This is only done to obtain the rough shape of the function; the correct values are found in the fitting phase as described in Chapter 2.3. The inter-system restraints positions and orientations are also calculated. The stiffness functions between the different systems are scaled according to a reference vehicle mass. Finally, all computed data is written to an xml-file which serves as an input file for MADYMO. It is important to bear in mind that the vehicle models are designed for frontal impact. This means that all choices made to build the structures are done to describe frontal impact as accurately as possible.

In the following paragraphs, a brief explanation is presented of every vehicle part that is used in the model. All choices made according to crush modes, number of bodies, joints and stiffness functions are explained.

2.2.1 Compartment and Firewall

The compartment offers a survival space for the occupants. Compartment collapse should therefore be avoided; thus the last decade showed a trend towards stiffer compartments [Ewens 2004] (Figure 2.2). This trend is shown in the majority of newly launched vehicle models. Because of this trend it is decided to model the compartment as undeformable. The compartment is mounted on the vehicle COG, which serves as a reference point for the whole vehicle. The A-pillar, B-pillar and C-pillar are also modelled with ellipsoids. A very important part of the compartment is the firewall. In a severe crash situation in which the engine is moved, the engine will hit the firewall, resulting in compartment intrusion. Measurement data of the location of the vertical part of the firewall are available. The firewall is thus modelled with a body and a single plate connected to the COG with a translational joint. The plate might be given a force penetration characteristic and the translational joint an initial stiffness characteristic. However, taking into account modern vehicle design this option was neglected.

Figure 2.2: Left: Model year 2000 Seat Ibiza which suffers from severe compartment deformation noticeable by the A-pillar collapse and the front wheel displacement. Right: Model year 2003 Seat Ibiza with minimal compartment deformation [Euro NCAP 2013].

2.2.2 Longitudinals

The longitudinals are the most energy absorbing structures and therefore the most complex crush structures of the vehicles. Since these vehicles are a simplified model of the actual car, it is chosen to model the longitudinals as a straight beam. The main challenge for the longitudinals is that the combined crush and bend effect in the structures is complicated to describe accurately. The beam element is in most scenarios crushed first followed by a bending phase. This effect is difficult to model with the available joints in MADYMO because the bending stiffness actually depends on the amount of deformation. MADYMO is only able to adjust the stiffness characteristic during the calculation process in a complex manner and since these are simplistic models, this is not a desirable solution. A more practical solution in MADYMO is to use a translational joint and a universal joint in series which is able to combine crush (translational) and bending (universal), however, the decline in bending stiffness after crush cannot be described and it is therefore assumed to be constant. The longitudinal is constructed using a minimum of six bodies, where the maximum length of each body is 0.2 meter. They are geometrically described by their height, width, length and distance between each other (left and right)

2.2.3 Bumper Beam

In general, the bumper beam has the potential of playing an important role in the vehicle crash since it connects the two longitudinals and will be important in the fitting process. The bumper is modelled as a straight beam using eight bodies as a default value and is connected by spherical joints. The stiffness function is adapted to design very stiff or weaker bumper beams. Depending on the vehicle type this is an important parameter in the fitting procedure as will be explained in the next chapter. It is assumed that the bending stiffness around the y-axis is proportional to the bending stiffness around the z-axis. A beam's bending stiffness is considered to be:

$$S = \frac{1}{12} * b * h^3 .$$

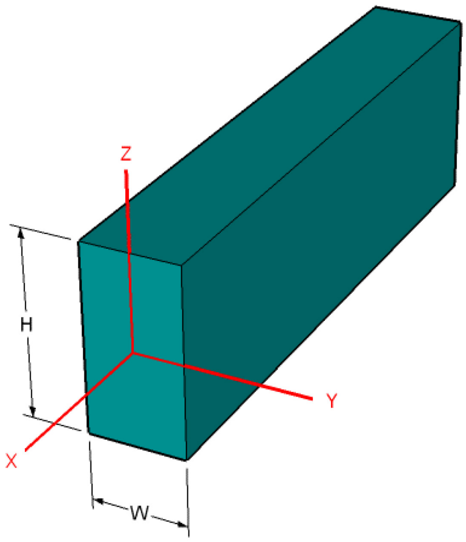

Figure 2.3: The bending stiffness for a beam around the y-axis is proportional to the stiffness around the z-axis.

This means if the height is twice the width of the beam, the stiffness around the y-axis is eight times the stiffness around the z-axis (Figure 2.3). The bumper is geometrically described by its height, width, length, distance to the floor and distance to the wheel axis.

2.2.4 Shotguns

For the shotguns, a similar approach is followed as is used in the longitudinals. They are constructed as a straight beam using six bodies as a default value and are connected with translational-universal joints. The shotguns are geometrically described by their height, width, length, distance between each other (left and right) distance to the floor and distance to the wheel axis.

2.2.5 Higher Crossbeam

For the higher crossbeam, a similar approach is used as in the bumper beam. The higher crossbeam is modelled as a straight beam using eight bodies as a default value and is connected by spherical joints. The higher crossbeam connects to the bumper and both the shotguns. The higher crossbeam is geometrically described by its height, width, length, distance to the floor and distance to the wheel axis.

2.2.6 Subframe

The short subframe is designed using six bodies (default, but customable) connected with spherical joints. It is connected with the longitudinals using point restraints. The wheels are connected to the arms of the subframe using spherical joints. The subframe is geometrically described by its width, length, height in the middle and distance to the floor in the middle.

2.2.7 Engine and Gearbox

Two types of engines are distinguished. Longitudinal engines are positioned in the axial direction, with the transmission located behind the engine. Transversal engines are positioned transversal to the vehicle axis and the gearbox is located next to the engine. The engine and gearbox are modelled with one distinct body each. They are connected to each other by bracket joints since the engine and gearbox system is regarded as being rigid. The engine is mounted to the subframe and longitudinals using point restraints. The engine and gearbox are geometrically described by their type, height, width, length, distance to wheel axis, distance to floor and distance from the centre.

2.3 Fitting the Vehicle Models Crash Response

The vehicle models created in the previous chapter have to be tuned to fit with a real live vehicle crash. The fitting procedure starts with fitting the multi-body vehicle model to the crash pulse from an FWRB impact. The stiffness functions of the different restraints and contact characteristics are used to fit the crash pulse from simulations onto the results obtained in real live FWRB test. This is done by combing matlab and MADYMO, where matlab determines the quality of the fit and adjusting the stiffnesses, whereas MADYMO is controlled by matlab to run the simulations.

2.3.1 Fitting Strategy

Fitting is done in three stages. The initial curve is fitted roughly onto the reference curve in the first stage whereby only the most influencing parameters are varied. Next the curve is split into several parts and fitting is done for the parts separately. Finally, fine tuning is done in a second stage in which fifty parameters are varied to obtain the best possible solution. These distinct stages are explained in this section

2.3.1.1 Initial Fit

It is found that the most important parameters of influence on the rough shape of the curve are stiffness functions regarding the longitudinals, engine, shotguns and subframe. In this stage it is only important to get the acceleration peak and timing in the same order as the reference crash pulse (Figure 2.4). This is done because it will substantially reduce the time needed in the next part of the fitting process. This is achieved by changing the stiffness functions mentioned above to get a decent enough fit.

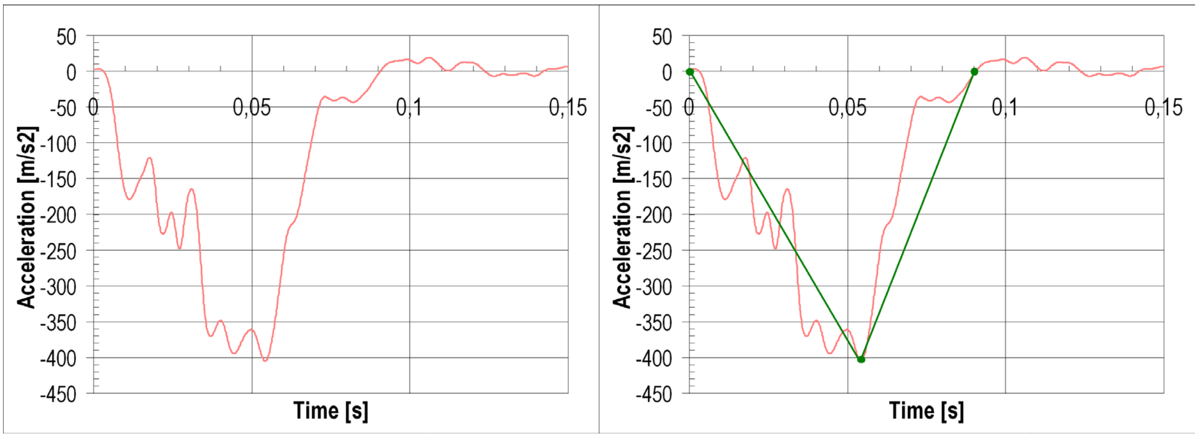

Figure 2.4: FWRB crash pulse (left) and the initial shape fitting points (right).

2.3.1.2 Second Stage

In the second stage the separate sections of the crash are fitted. First, the separate sections are detected by a simple peak detection algorithm, where each section between the peaks represents a unique combination of energy absorbing crash structures (Figure 2.5). A standard order of these crash structures is assumed in order to fit the shape of the deceleration crash pulse. When a different order is expected, a video analysis is done to find the correct crash structures for the corresponding sections during the crash.

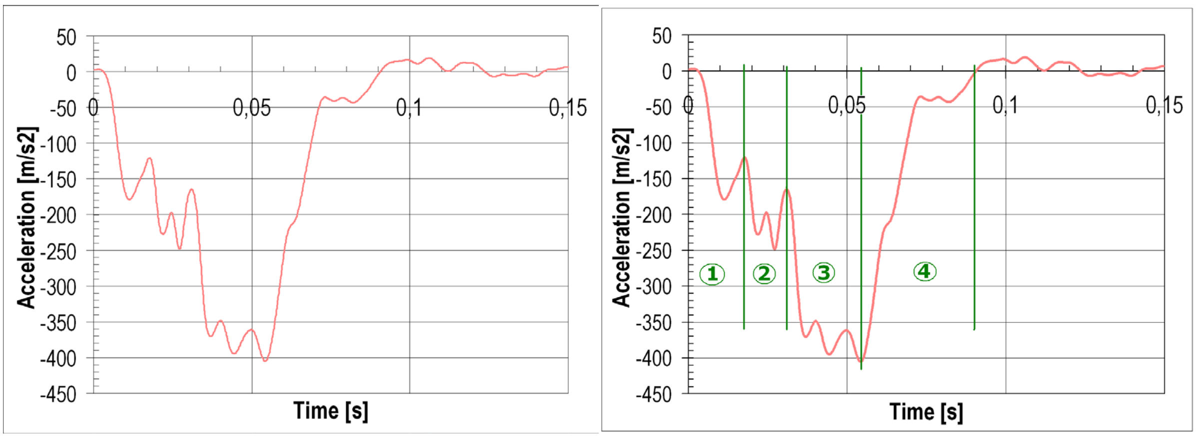

Figure 2.5: FWRB crash pulse (left) and different crash sections during the crash (right).

The iterative fitting process is done with the crash structures active in the corresponding section. A least square method is used to find the closest shape in that separate section. It is computed considering every data point. The outcome of the least squares solution approaches to zero when the solution improves. The least squares solution is given by:

$$ls = \frac{\sqrt{\sum_{i=1}^{N} da_i^{\,2}}}{N} \qquad (3.1)$$

In which ls is the least squares solution, da_i is the distance between the reference signal and the solution, and N is the number of data points. Furthermore a 90 percentile corridor is used to make sure that for each point a certain close enough value is reached. After each section the effect is also measured and controlled in the section before. This is done in order to keep the entire shape as close as possible.

2.3.1.3 Fine Tuning

Aim of the second fitting stage is to fine-tune the result of the second stage. For fine-tuning it is desired to vary all parameters that influence each other at the same moment. It is desired to evaluate every possible combination of parameters. Since this will result in a too large number of simulations, it is chosen to limit to the parameters used in the second stage and closely vary around the values found.

3 ACTUAL VEHICLE MODEL CREATION

The generic vehicle modelling procedure, which has been developed in FIMCAR, was used as a basis for designing different MADYMO vehicle models to establish a vehicle fleet.

Due to limited amount of available geometric data sets only a limited amount of models could be built. A MADYMO model of the vehicles below was generated:

1. Supermini referred to as Supermini 2
2. Small family car referred to as Small Family Car 2
3. SUV referred to as SUV 4

3.1 General

Chapter 2 showed that it is possible to construct and fit simple vehicle crash models in a generic manner. Based on geometrical data a base MADYMO model was generated. This base model was used to tune the model characteristics to match a Full Width Rigid Barrier test (FWRB). Fitting of vehicle models was done by an iterative process of the adaptation of the stiffness functions with focus on matching the velocity and displacement profile. Once the model reaches an acceptable level of correlation those models are used to verify the performance with the Euro NCAP Offset Deformable Barrier (ODB) configuration.

It should be taken into account that the created models have some limitations due to the assumptions made:

- The occupant compartment of the model is rigid, therefore no intrusion of the occupant compartment has been assumed.
- Vertical misalignment has not been evaluated as current vehicle models are not suited for this.
- No dummy injury assessment, as dummy injury assessment is not feasible, since there is:
    - No interior available
    - No restraint system information
    - No trigger information
    - No seat and floor structural information
    - No steering wheel, steering column, knee bolster information

For the crash severity evaluations the Vehicle Pulse Index (VPI) [ISO 2013] is used, in which higher values represent a lower crash performance with higher risk of occupant injury.

$$M\ddot{y} + ky = P(t)$$

where

$$P(t) = \begin{cases} 0, & x < s \\ k(x-s), & x \geq s \end{cases}$$

$$VPI = \max(\ddot{y})$$

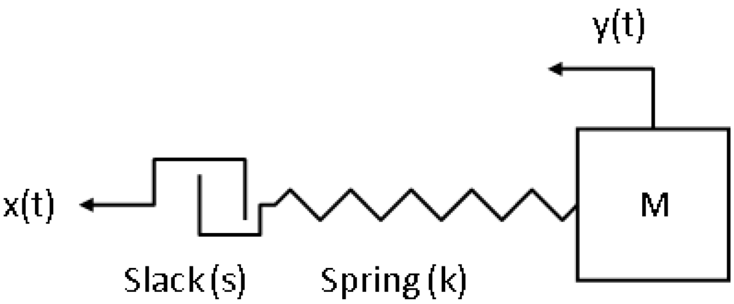

Figure 3.1: Vehicle Pulse Index (VPI).

With a mass of 1 kg and the by Volvo recommended values of; k = 2500 N/m and s = 0.03m.

3.2 Supermini 2

The created model for the Supermini 2 based on the provided geometrical data can be seen below in Figure 3.2.

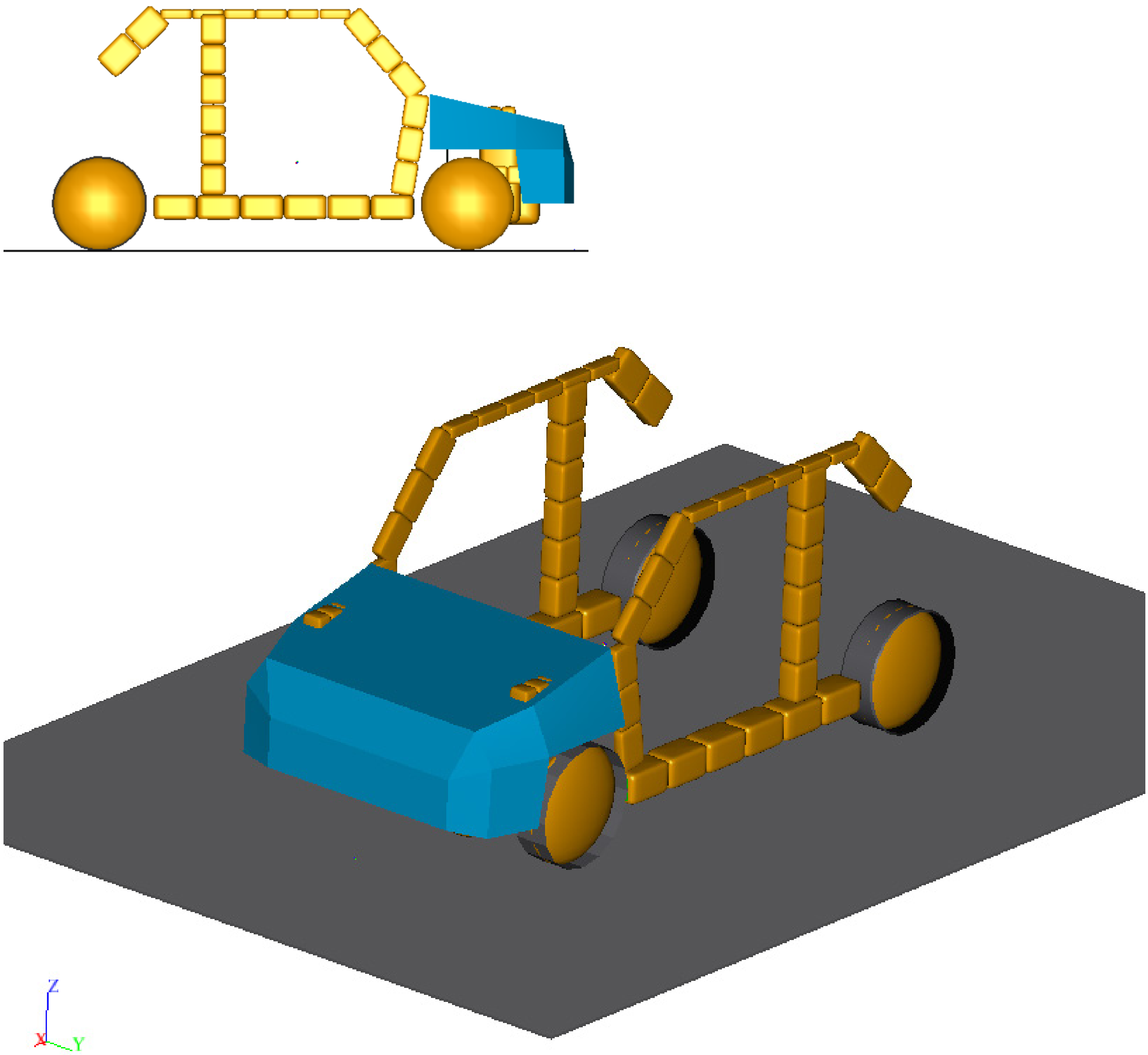

Figure 3.2: Model set-up of Supermini 2.

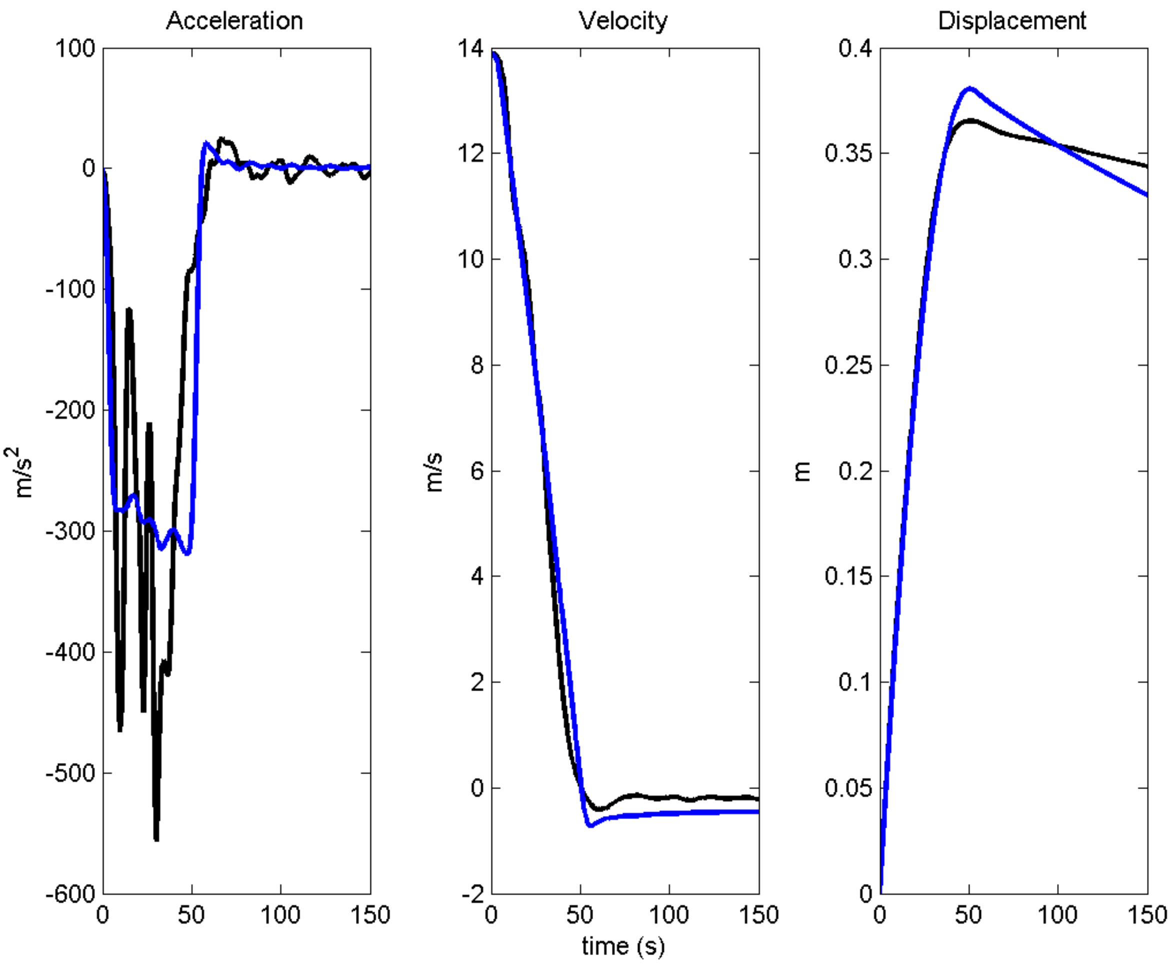

Figure 3.3: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar Supermini 2.

The base model of the Supermini 2 was tuned with the test data of the Full Width Rigid Barrier (FWRB) test. Figure 3.3 shows the acceleration, velocity and displacement over time for the FWRB test (black) as the simulation (blue) of the final Supermini 2 model. During the tuning the focus was directed towards the velocity profile of the left lower B-pillar. The final Supermini 2 simulation model shows a similar velocity curve as observed in the FWRB test.

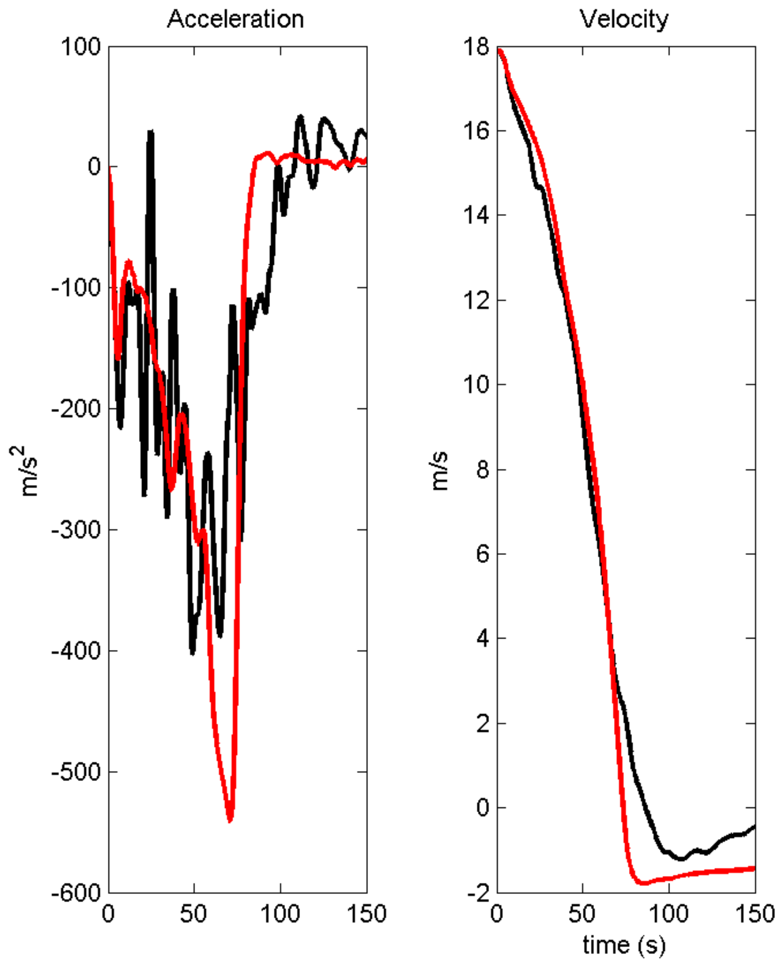

Figure 3.4: Correlation ODB test (black) vs. simulation (red) left lower B-pillar Supermini 2.

To check model performance a simulation of Offset Deformable Barrier (ODB) was performed, which has been compared to the ODB test data. Figure 3.4 shows the ODB test (black) and simulation (red) results for the Supermini 2.

3.3 Small Family Car 2

The created model for the Small Family Car 2 based on the provided geometrical data is shown in Figure 3.5.

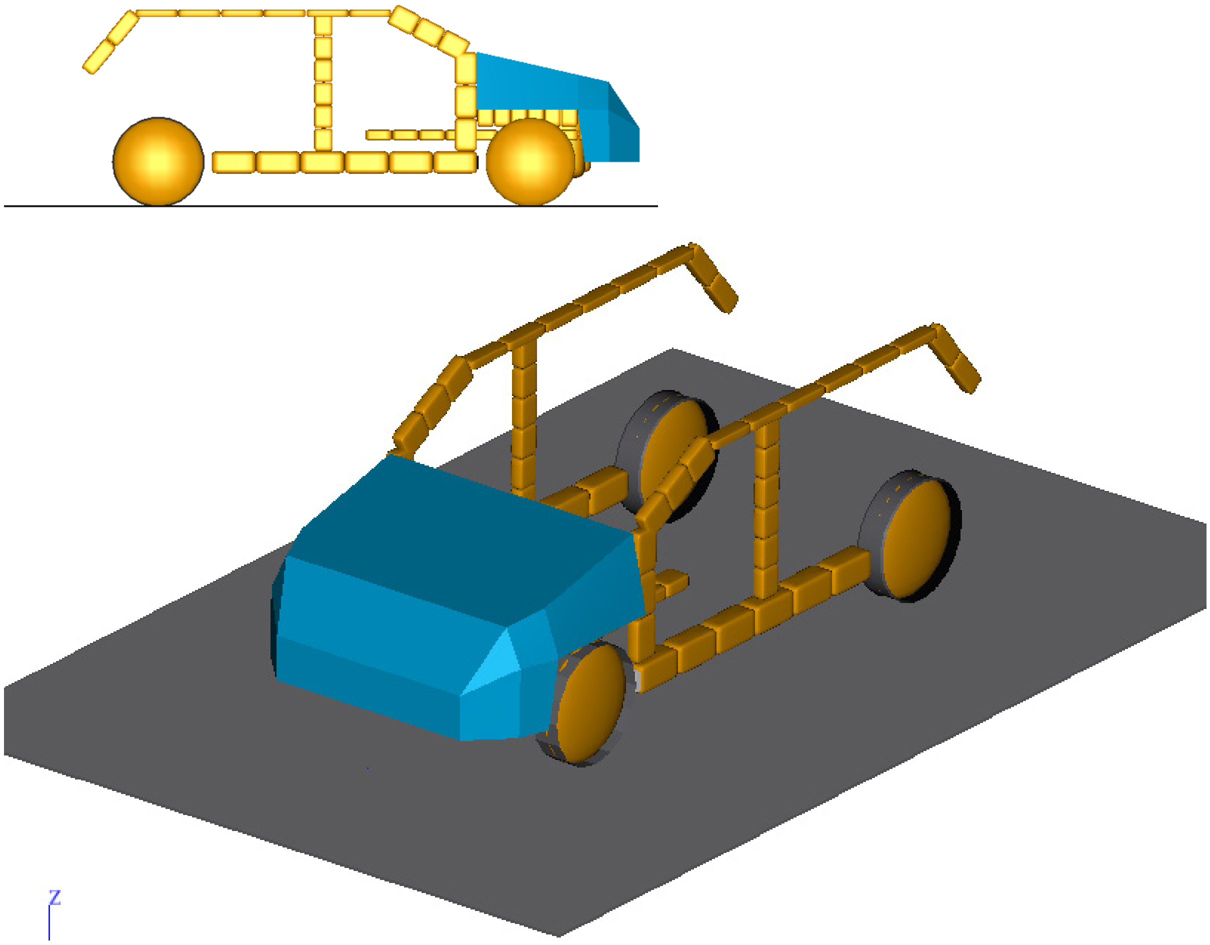

Figure 3.5: Model set-up of Small Family Car 2.

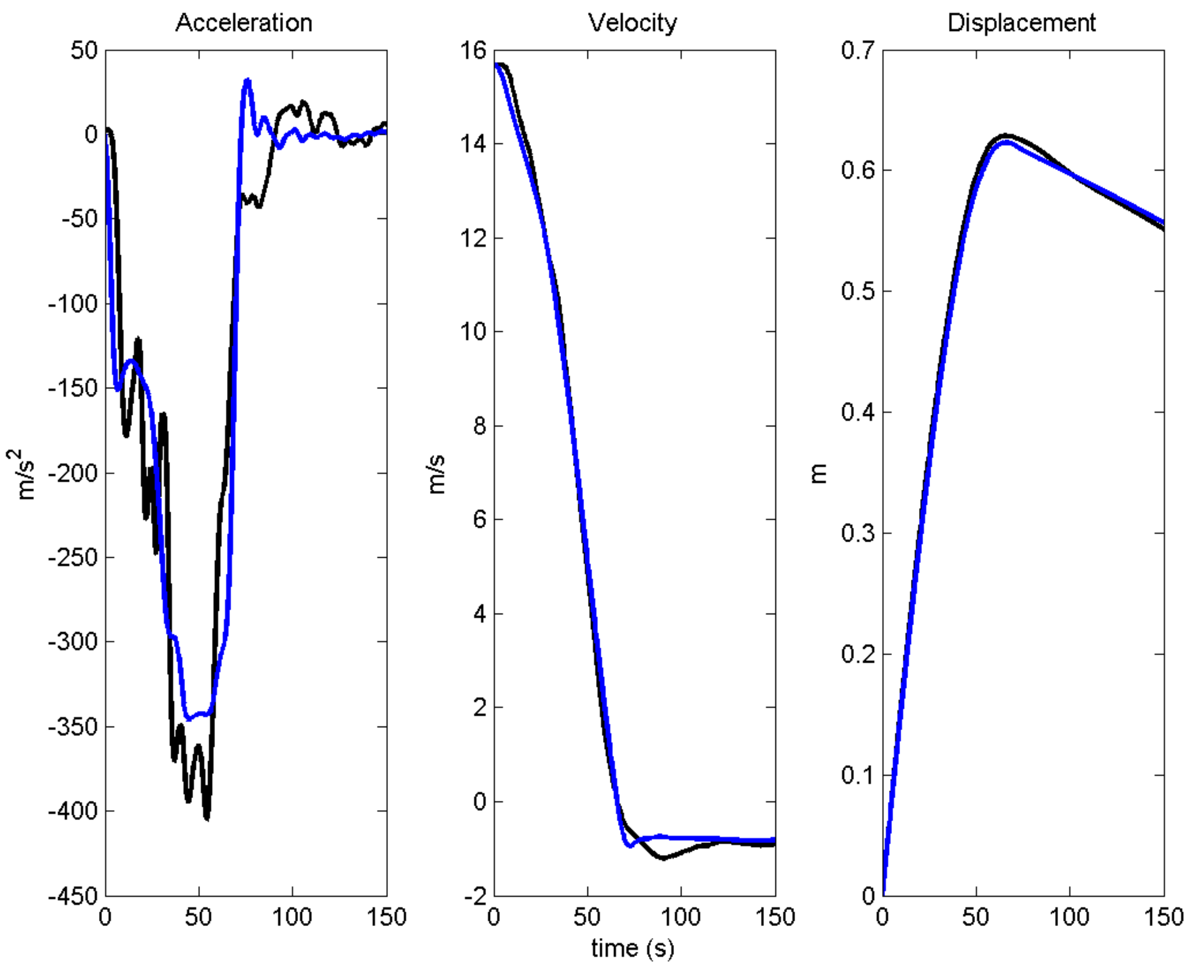

Figure 3.6: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar Small Family Car 2.

Figure 3.6 shows the acceleration, velocity and displacement over time for the Full Width Rigid Barrier (FWRB) test (black) as the simulation (blue) of the final Small Family Car 2 model. The model was created by tuning the simulation with test of the FWRB. The tuning focuses on the velocity profile of the left lower B-pillar. The final model of the Small Family Car 2 has a similar velocity profile compared to the FWRB test.

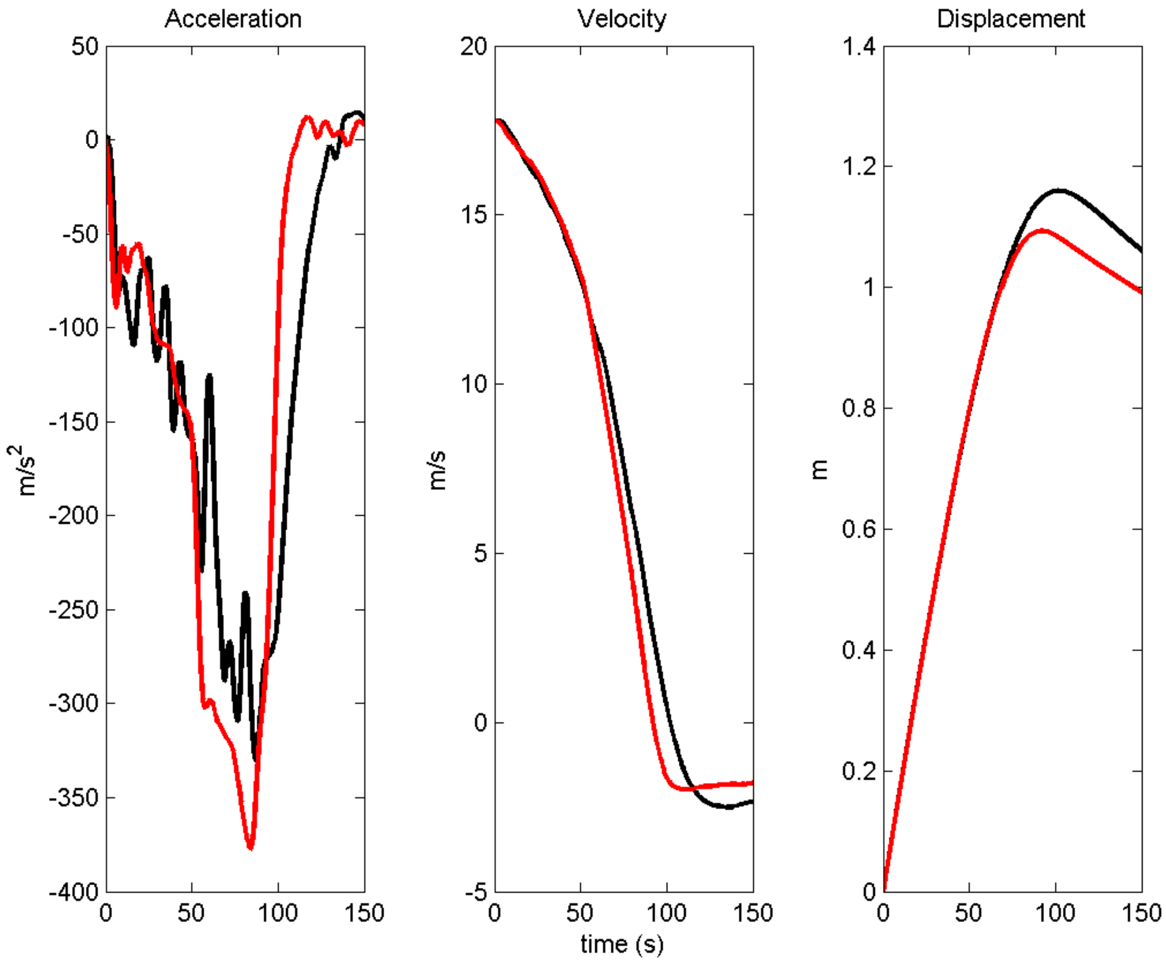

Figure 3.7: Correlation ODB test (black) vs. simulation (red) left lower B-pillar Small Family Car 2.

To check model quality also test and simulation of Offset Deformable Barrier (ODB) test have been compared. Figure 3.7 shows the ODB test (black) and simulation (red) for the Small Family Car 2.

3.4 SUV 4

The model of the SUV 4, which was created based on the provided geometrical data, can be observed in Figure 3.8.

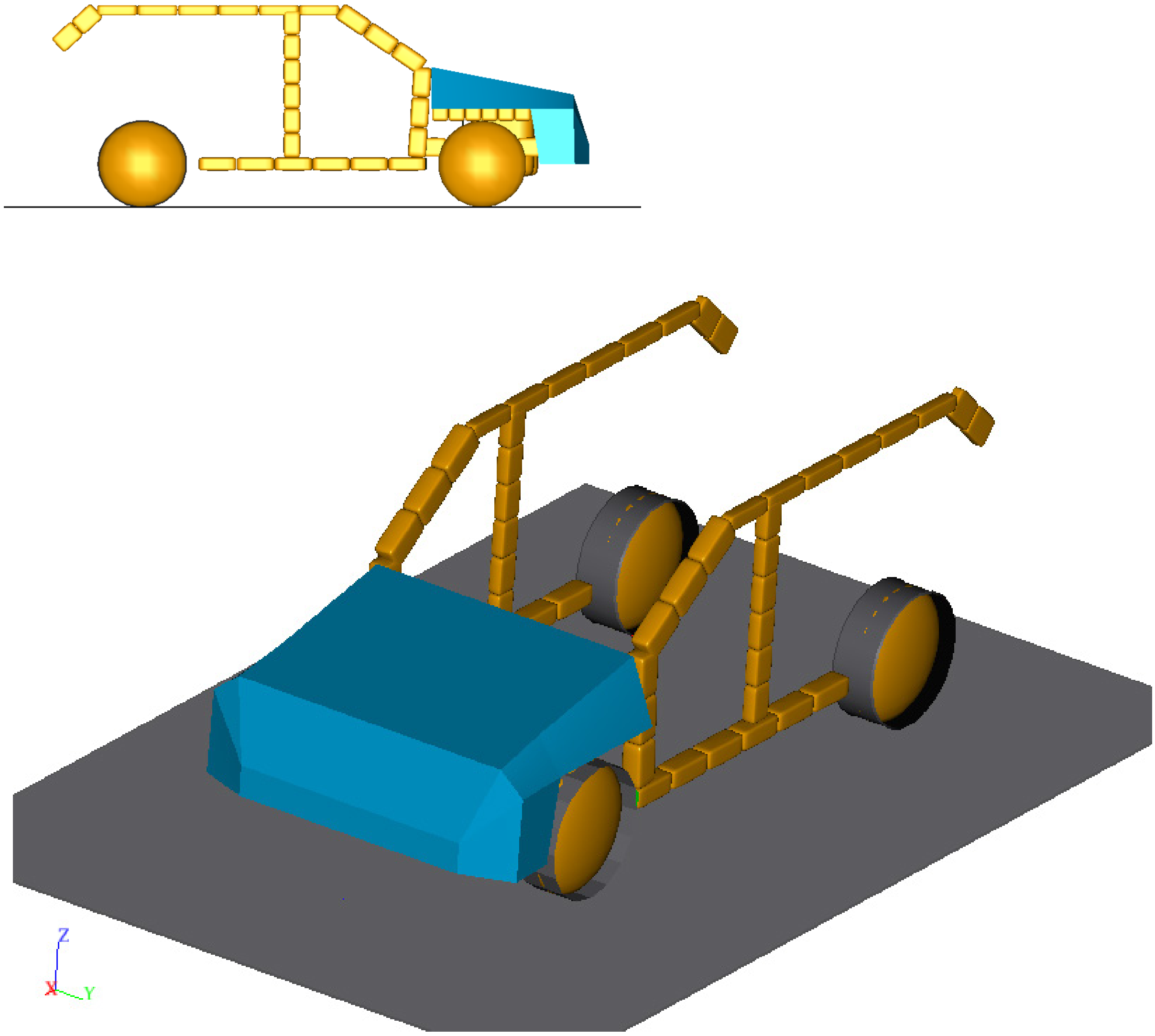

Figure 3.8: Model set-up of SUV 4.

Also the base model of the SUV 4 was tuned with Full Width Rigid Barrier (FWRB) test data. Figure 3.9 shows the acceleration, velocity and displacement of the left lower B-pillar over time for the FWRB test (black) as the simulation (blue) of the final SUV 4 model. A similar velocity profile can be observed in FWRB test and simulation.

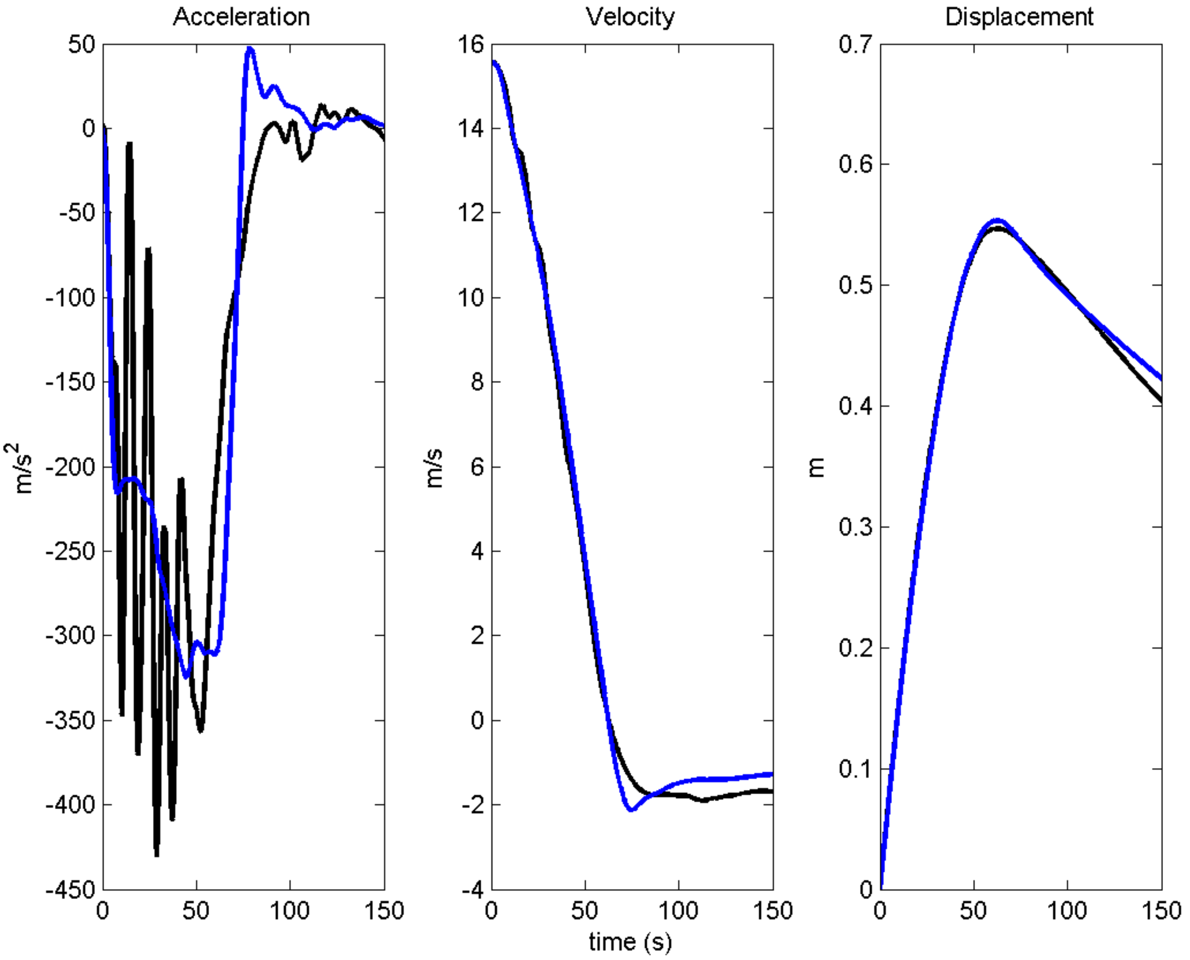

Figure 3.9: Correlation FWRB test (black) vs. simulation (blue) left lower B-pillar SUV 4.

Also for the SUV 4 the Offset Deformable Barrier (ODB) check was performed. Figure 3.10 shows the ODB test (black) and simulation (red) for the SUV 4.

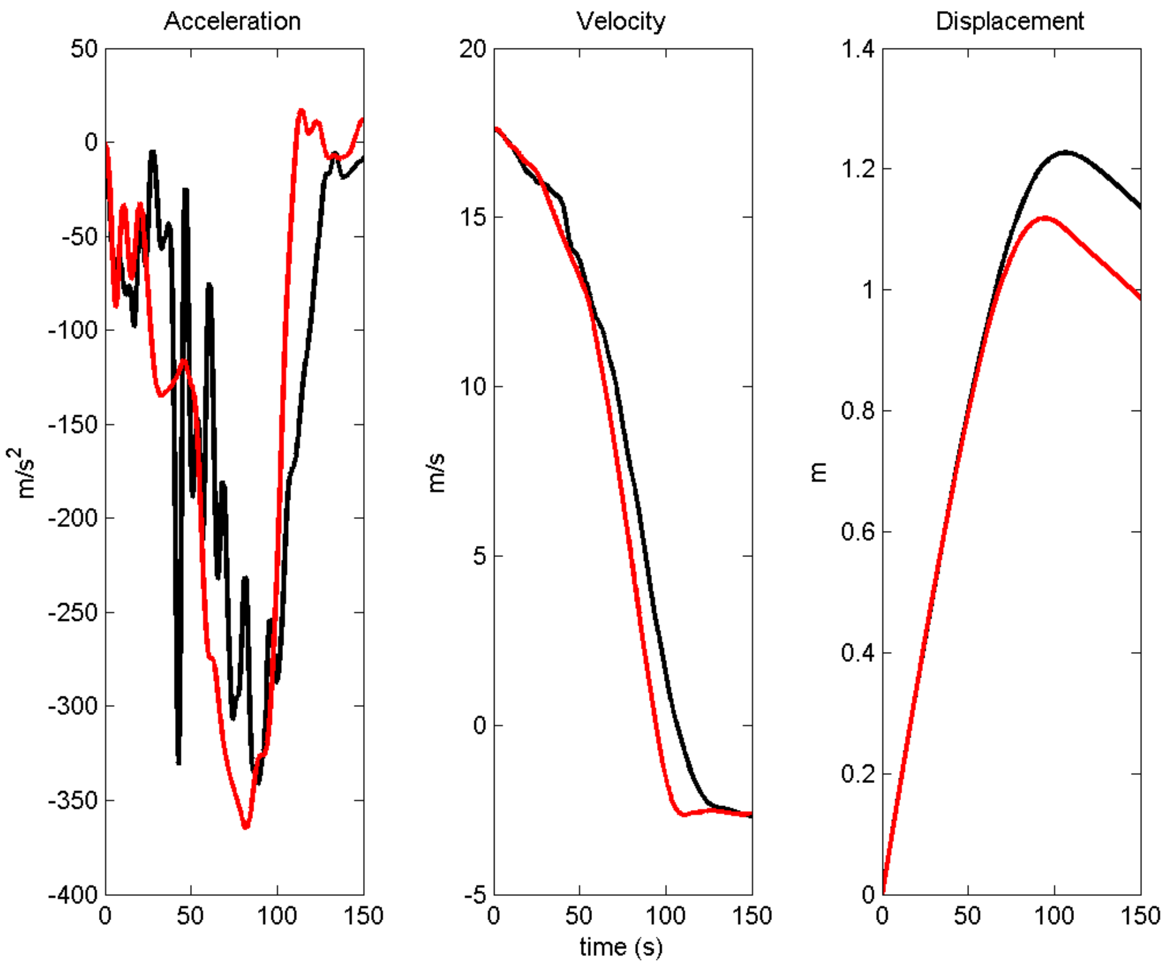

Figure 3.10: Correlation ODB test (black) vs. simulation (red) left lower B-pillar SUV 4.

4 FLEET STUDY ANALYSIS

Two separate fleet studies were performed, the initial one with all available models to evaluate a large set of variables with a largest possible set of vehicles. The second fleet study focussed on the evaluation of the specific phenomena of longitudinal stiffness and cross beam failure and is performed with a selection of vehicles.

4.1 Fleet Study I

4.1.1 Set-up I

4.1.1.1 Vehicles I

For the initial study a large spread of vehicle configurations was used to have the largest possible representation of the actual vehicle fleet. All available vehicle models were used, so the Supermini 2, the Small Family Car 2 and the SUV 4. In order to compensate for the limited amount of evaluated vehicle masses an extra parameter was added in which the vehicle mass was adjusted. In this way also the gaps between the evaluated vehicles were covered.

4.1.1.2 Input Variables I

- **Mass of vehicle 1** 3 settings per vehicle
  - Supermini 2 -75kg test mass (1159 kg) +150 kg (2 occupants)
  - Small Family Car 2 -75kg test mass (1309 kg) +225 kg (3 occupants)
  - SUV 4 -75kg test mass (2255 kg) +375 kg (5 occupants)
- **Speed**
  - 40 km/h for both vehicles
  - 56 km/h for both vehicles
- **Misalignment**
  - 50% overlap of vehicle 1
  - 100%
- **Strength longitudinal of vehicle 1**
  - x1 (represents longitudinal standard vehicle)
  - x1.5 (represents stiffness x1.5 of longitudinal standard vehicle)
- **Strength cross beam of vehicle 1**
  - x1 (represents connected cross beam)
  - x0.001 (represents cross beam failure)

4.1.1.3 Output Parameter I

Various output parameters were available.

- Acceleration of B-pillar bottom left and right
- Velocity of B-pillar bottom left and right
- Displacement of B-pillar bottom left and right
- Max ΔV of B-pillar bottom left
- Max mean acceleration (= max ΔV / time to max ΔV) of B-pillar bottom left
- ASI (Acceleration Severity Index) of B-pillar bottom left [ECS 1995], see Figure 4.1
- VPI (Vehicle Pulse Index) of B-pillar bottom left [ISO 2013], see Figure 4.2

$$\mathrm{ASI}\,(t) = [(\bar{a}_x / \hat{a}_x)^2 + (\bar{a}_y / \hat{a}_y)^2 + (\bar{a}_z / \hat{a}_z)^2]^{1/2}$$

$$\hat{a}_x = 12\ \mathrm{g} \qquad \hat{a}_y = 9\ \mathrm{g} \qquad \hat{a}_z = 10\ \mathrm{g}$$

Figure 4.1: ASI calculation.

$$M\ddot{y} + ky = P(t)$$

where

$$P(t) = \begin{cases} 0, & x < s \\ k(x-s), & x \geq s \end{cases}$$

$$VPI = \max(\ddot{y})$$

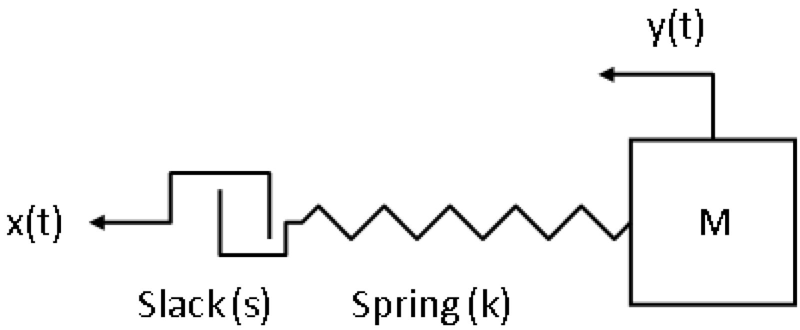

Figure 4.2: Vehicle Pulse Index (VPI).

With a mass of 1 kg and the by Volvo recommended values of; k = 2500 N/m and s = 0.03 m.

For the crash severity evaluations the Vehicle Pulse Index (VPI) is used, in which higher values represent a lower crash performance with higher risk of occupant injury.

4.1.1.4 Simulation Matrix I

A reduced matrix was evaluated based on selection below resulting in 162 simulations, see Table 1.

Equal vehicles	3 masses of vehicle 1
	2 equal speeds
	2 overlaps
	2 longitudinal strengths of vehicle 1 (long strengths)
	2 cross beam strengths of vehicle 1 (c-b strengths)
Different vehicles	both original test mass
	1 speed
	2 overlaps
	2 cross beam strengths (only for 50% overlap) (c-b strengths)

Table 1: Simulation matrix I

		Vehicle 2		
		Supermini 2	**Small Family Car 2**	**SUV 4**
Vehicle 1	**Supermini 2**	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths
	Small Family Car 2	40 km/h 50% 100% 2 c-b strengths	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths
	SUV 4	40 km/h 50% 100% 2 c-b strengths	40 km/h 50% 100% 2 c-b strengths	3 masses 2 speeds 2 overlap 2 long strengths 2 c-b strengths

4.1.2 Results I

4.1.2.1 Mass Dependency

In Figure 4.3 below an overview can be found of the VPI values of the various vehicle weights. The first 3 pictures show the results with equal vehicles, respectively Supermini 2, Small Family Car 2 and SUV 4. The last picture shows all simulations, i.e. as well the simulations with equal vehicles as with different vehicles. For each vehicle, the 3 mass variations are shown as described under input variables.

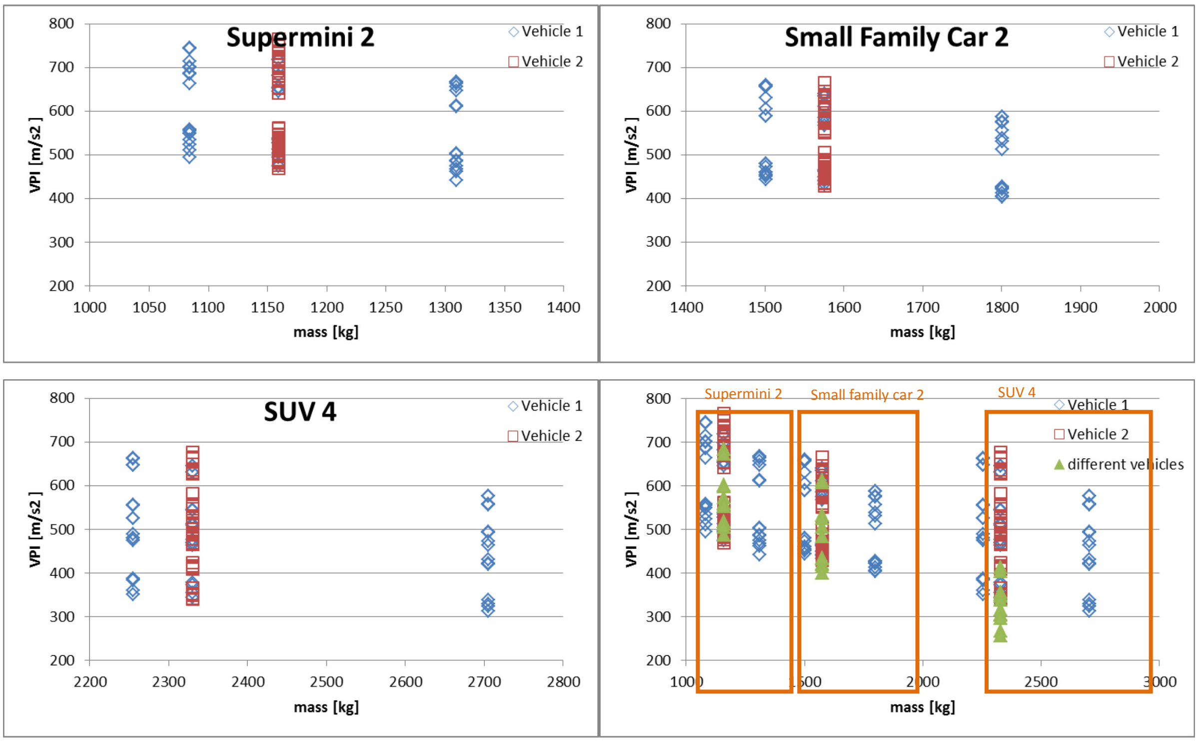

Figure 4.3: VPI of vehicle 1 and 2 in simulations with variable mass.

A clear difference can be observed in VPI for the difference between low (40km/h) and high (56km/h) impact speed. The pictures also demonstrate clearly that a higher mass of vehicle 1 results in lower VPI values for vehicle 1 and a higher VPI value for vehicle 2, where vehicle 1 and 2 are the same type.

The data of impacts with different vehicles (green triangles in right bottom corner picture) show average VPI's from high to low:

- Supermini 2 with SUV 4
- Small Family Car 2 with SUV 4
- Supermini 2 with Small Family Car 2
- Small Family Car 2 with Supermini 2
- SUV 4 with Small Family Car 2
- SUV 4 with Supermini 2

The much heavier SUV 4 compared to the Supermini 2 and Small Family Car 2 gives much higher VPI values for the opponent (Supermini 2 and Small Family Car 2), but lower VPI values for the SUV 4.

Overall, it can be stated that a higher vehicle mass results in lower VPI for that vehicle. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.

4.1.2.2 Longitudinal Stiffness

Figure 4.4 shows the 72 configurations (total 144 simulations) that were evaluated with default (x1) longitudinal and cases in which the longitudinals of vehicle 1 have an increased stiffness (x1.5). The left picture shows the VPI values of vehicle 1, with default (x1, blue) and higher (x1.5, red) longitudinal stiffness per configuration. In the right picture also the VPI of vehicle 2 is added.

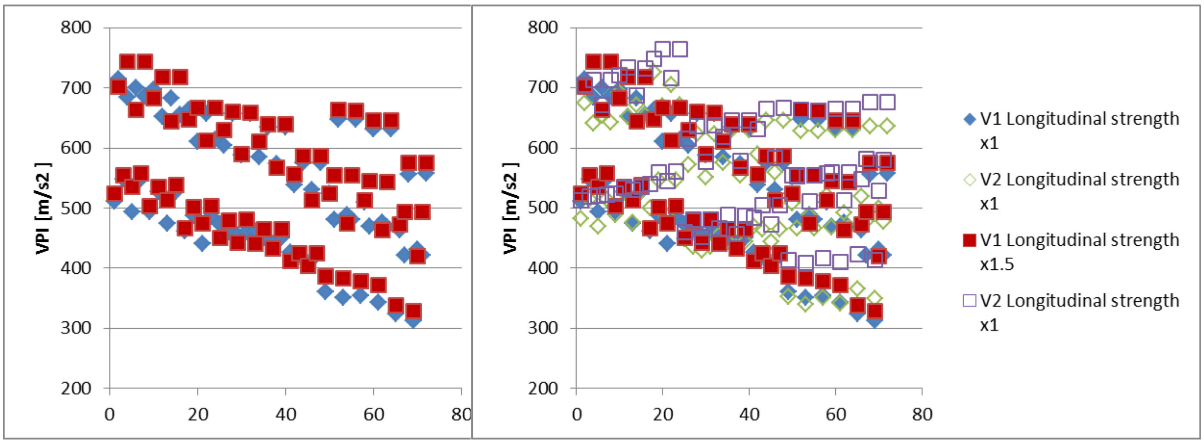

Figure 4.4: VPI of vehicle 1 and 2 in various longitudinal stiffness simulations.

Figure 4.4 shows that overall the stiffer (x1.5) longitudinals of vehicle 1 result in a higher VPI of vehicle 1 compared to vehicle 1 with the default (x1) stiffness. The effect on vehicle 2 however is overall larger. The VPI values of vehicle 2 for impact with opponent with stiffer (x1.5) longitudinal are significantly higher compared to opponent with default (x1) longitudinal stiffness.

Figure 4.5 shows a simulation of SUV 4 against SUV 4 with 100% overlap at 40 km/h, with green the default longitudinal stiffness (x1) and red the highest stiffness (x1.5), with connected cross beam.

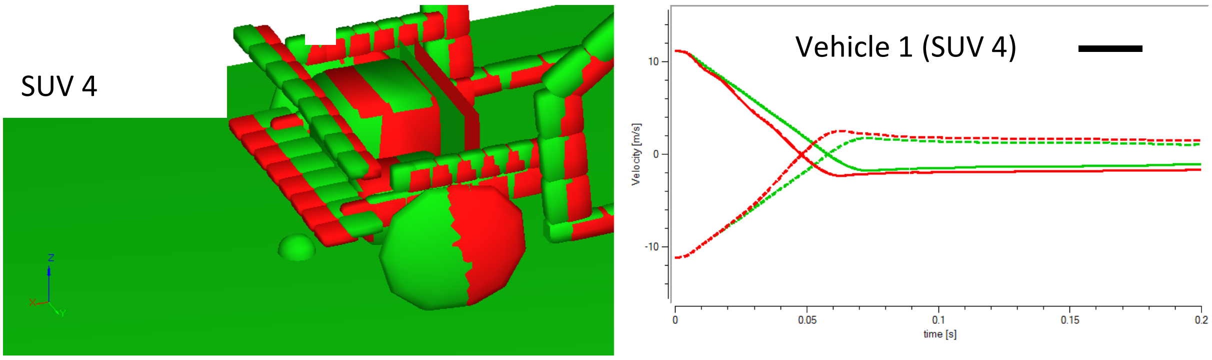

Figure 4.5: Default (x1) (green) and high (x1.5) (red) longitudinal stiffness simulation of SUV 4 - SUV 4.

Overall, it can be stated that a higher longitudinal stiffness results in higher VPI, for as well vehicle 1 with stiffer longitudinal, but even more for the opponent vehicle 2.

4.1.2.3 Cross Beam Failure

Figure 4.6 shows the 42 configurations (total 84 simulations) that were evaluated with cross beam connected and with cross beam failure in vehicle 1. Only 50% overlap configurations are taken into account. The left picture shows the VPI values of vehicle 1, with cross beam connected (blue) and failed per configuration (red). In the right picture also the VPI of vehicle 2 is added.

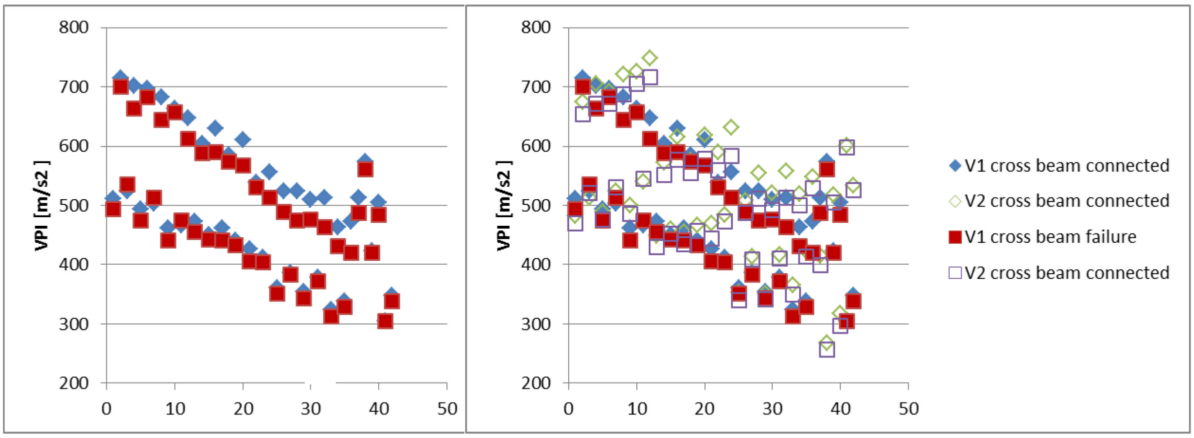

Figure 4.6: VPI of vehicle 1 and 2 in cross beam connected and failed simulations.

Figure 4.6 shows that overall the VPI is lower in case the cross beam fails (red) of vehicle 1 compared to vehicle 1 in which the cross beam does not fail (blue). This holds for as well vehicle 1 as vehicle 2. The overall stiffness of the vehicle increases if the cross beam does not fail, as also the longitudinal of the non-impacted side will be deformed.

A simulation of SUV 4 against SUV 4 with 50% overlap at 56km/h, with green the connected cross beam and red the failed cross beam simulation is shown in Figure 4.7.

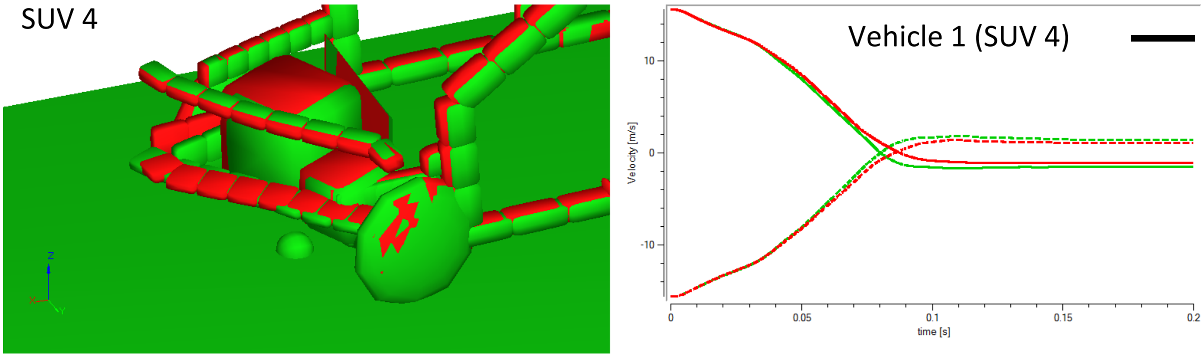

Figure 4.7: Cross beam connected (green) and cross beam failed (red) simulation of SUV 4 - SUV 4.

Overall, it can be stated that an impact with a vehicle that has cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle. However, it needs to be noted that phenomena like intrusion resulting from the cross beam failure are not considered in the simulation. Therefore the VPI might give a wrong estimation of the dummy loadings.

4.2 Fleet Study II

4.2.1 Set-up II

4.2.1.1 Vehicles II

The focus of the second part of the fleet study was to evaluate the longitudinal stiffness and the failure of the cross beam. This was done with the Supermini 2 and SUV 4. The possible failure of the cross beam has been implemented for the Supermini 2.

4.2.1.2 Input Variables II

Fixed variables:

- **Mass**
  - Supermini 2 test mass (1159 kg)
  - SUV 4 test mass (2255 kg)
- **Misalignment**
  - 50% overlap of vehicle 1 (Supermini 2)
- **Speed**
  - 56 km/h for both vehicles

Variables:

- **Strength longitudinal**
  - Supermini 2 150% - 50% (10% steps, 11 levels)
  - SUV 4 100% - 50% (10% steps, 6 levels)
- **Strength cross beam of vehicle 1 (Supermini 2)**
  - x1 (represents connected cross beam)
  - x0.001 (represents cross beam failure)

4.2.1.3 Output Parameter II

Various output parameters were available.

- Acceleration of B-pillar bottom left and right
- Velocity of B-pillar bottom left and right
- Displacement of B-pillar bottom left and right
- Max ΔV of B-pillar bottom left
- Max mean acceleration (= max ΔV / time to max ΔV) of B-pillar bottom left
- ASI (Acceleration Severity Index) of B-pillar bottom left [ECS 1995], see Figure 4.1
- VPI (Vehicle Pulse Index) of B-pillar bottom left [ISO 2013], see Figure 4.2

4.2.1.4 Simulation Matrix II

A full matrix has been evaluated, resulting in 132 simulations, see also Table 2.

Different vehicles both original test mass
1 speed

1 overlap
11 longitudinal strengths of vehicle 1 (long strengths)
6 longitudinal strengths of vehicle 2 (long strengths)
2 cross beam strengths of vehicle 1 (c-b strengths)

Table 2: Simulation matrix II.

		Vehicle 2
		SUV 4
Vehicle 1	**Supermini 2**	test masses 56 km/h 50% overlap 11 x 6 long strengths 2 c-b strengths

4.2.2 Results II

4.2.2.1 Longitudinal Stiffness

Two sets of each 66 simulations (11x6) were performed, one in which the cross beam stays connected and one in which the cross beam fails for vehicle 1. First the effect of the stiffness variation of the longitudinal will be discussed. The longitudinal stiffness of vehicle 1 (Supermini 2) various between low stiffness (x0.5) and high stiffness (x1.5), for vehicle 2 (SUV 4) between low stiffness (x0.5) and default stiffness (x1).

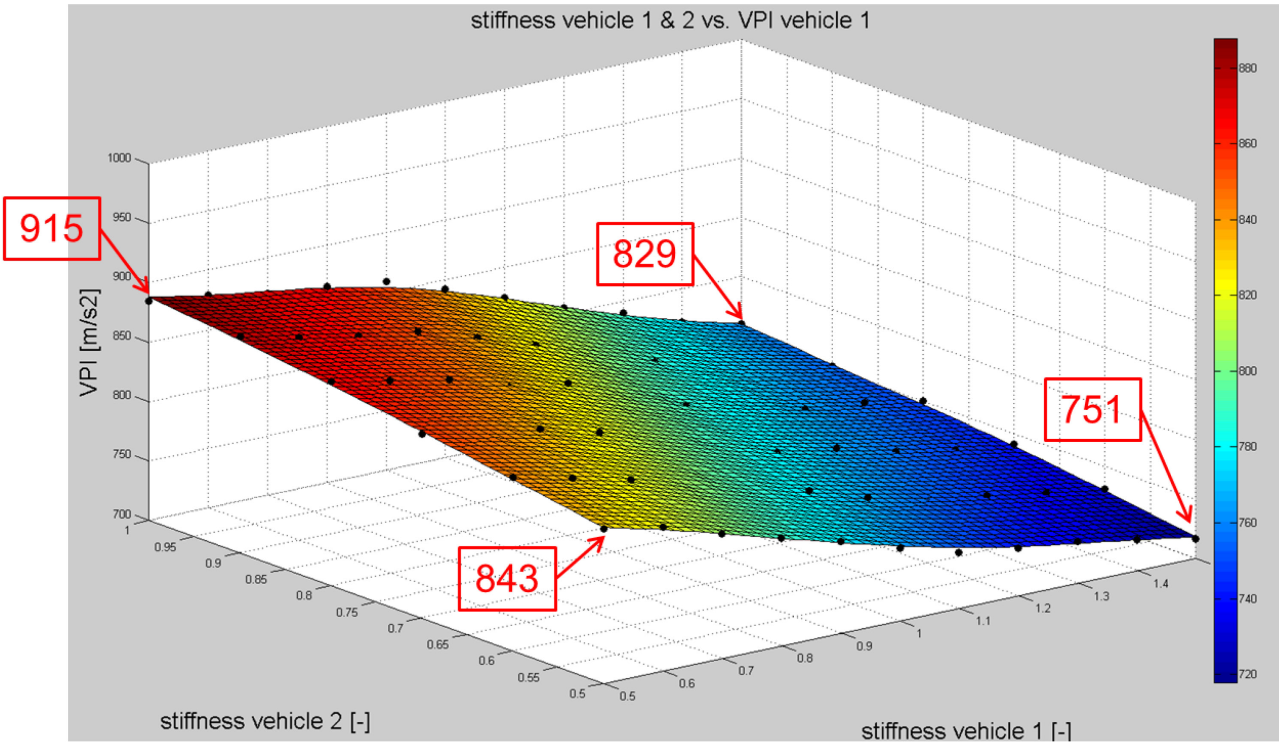

Figure 4.8: VPI of Supermini 2 for simulations with connected cross beam.

Figure 4.8 shows the fitted surface of the VPI of vehicle 1 (Supermini 2) to the simulations (black dots) with the connected cross beam, showing the highest VPI (915m/s^2) for the impact of the Supermini 2 with lowest longitudinal stiffness (x0.5) and SUV 4 with default (highest) longitudinal stiffness (x1). The lowest VPI (751m/s^2) occurs with the Supermini 2 with highest longitudinal stiffness (x1.5) and SUV 4 with lowest longitudinal stiffness (x0.5).

The VPI of vehicle 1 (Supermini 2, purple) and vehicle 2 (SUV 4, green), both with connected cross beam is shown in Figure 4.9. This clearly shows that the VPI values of the Supermini 2 (min.: 751m/s^2) are always well above the VPI values of the SUV 4 (max.: 429m/s^2), even with the increased longitudinal stiffness of the Supermini 2 (x1.5) and the reduced longitudinal stiffness of the SUV 4 (x0.5).

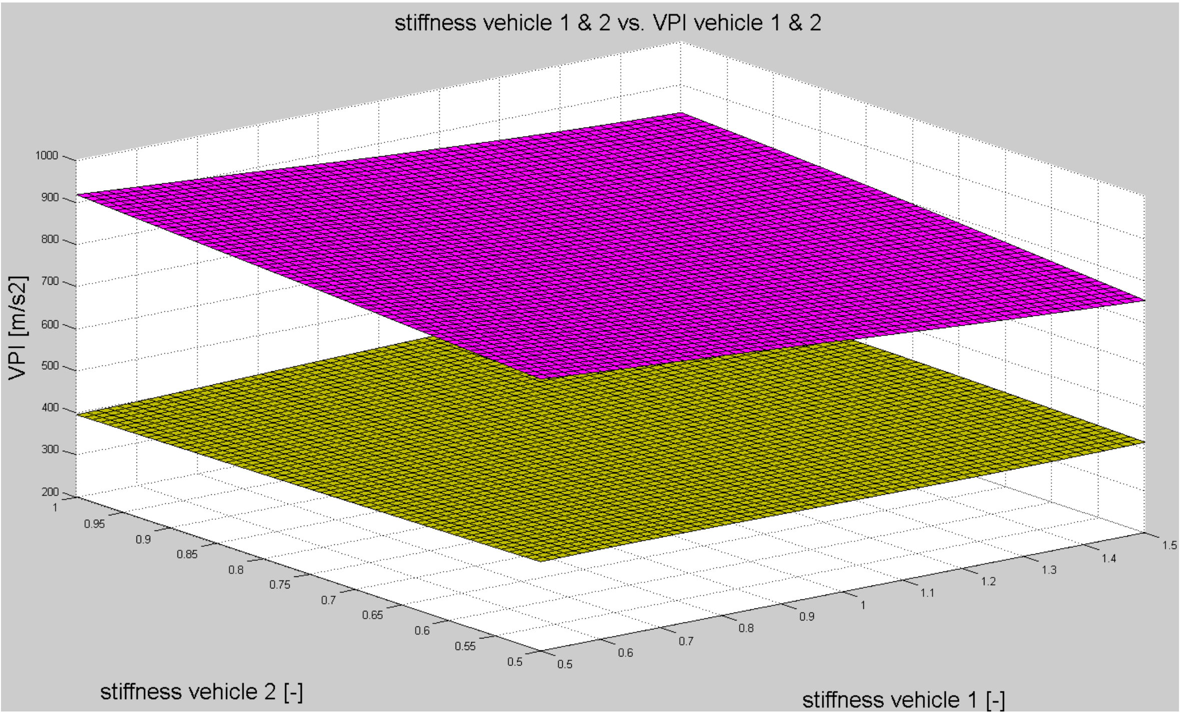

Figure 4.9: VPI of Supermini 2 (purple) and SUV 4 (green) for simulations with connected cross beam.

Figure 4.10 shows a simulation of Supermini 2 against default SUV 4 with 50% overlap at 56 km/h, with green the lowest longitudinal stiffness (x0.5) and red the highest stiffness (x1.5) for the Supermini 2.

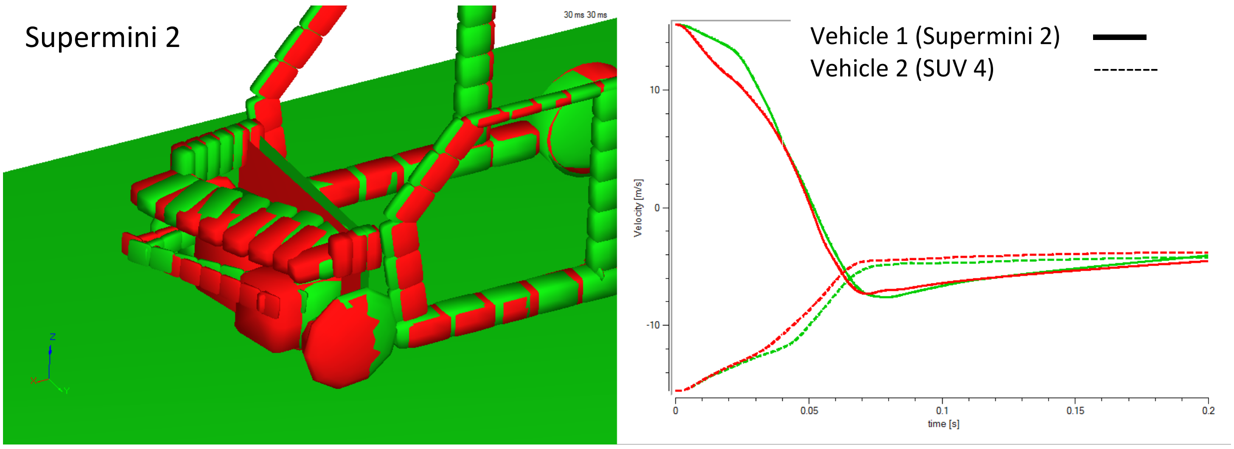

Figure 4.10: Low (x0.5, green) and high (x1.5, red) longitudinal stiffness simulation of Supermini 2 - SUV 4.

Fleet study II shows:

- Significant difference (close to 100m/s2) in VPI of vehicle 1 (Supermini 2) between decreased (x0.5) and increased (x1.5) longitudinal strength for vehicle 1 (Supermini 2).
- Significant difference (close to 100m/s2) in VPI of vehicle 1 (Supermini 2) between decreased (x0.5) and standard (x1) longitudinal strength for vehicle 2 (SUV 4).

Similar to fleet study I, this fleet study demonstrates that a higher longitudinal stiffness results in higher VPI for vehicle 1 (Supermini 2) with stiffer longitudinal.

4.2.2.2 Cross Beam Failure

Two sets of each 66 simulations (11x6) have been performed, one in which the cross beam stays connected and one in which the cross beam fails for vehicle 1 (Supermini 2).

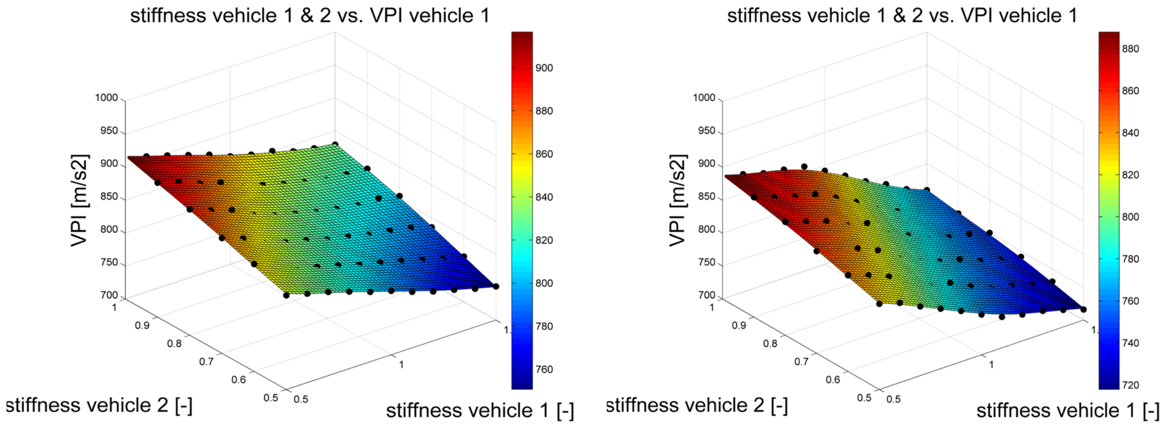

Figure 4.11: VPI of Supermini 2 with connected cross beam (left) and cross beam failure (right).

Figure 4.11 demonstrates the fitted surface of the VPI of vehicle 1 (Supermini 2) to the simulations (black dots) with the connected cross beam (left) and cross beam failure (right).

Figure 4.12 shows that the VPI of vehicle 1 (Supermini 2) with connected cross beam (green) exceeds the VPI values of vehicle 1 (Supermini 2) with cross beam failure over the entire evaluated area.

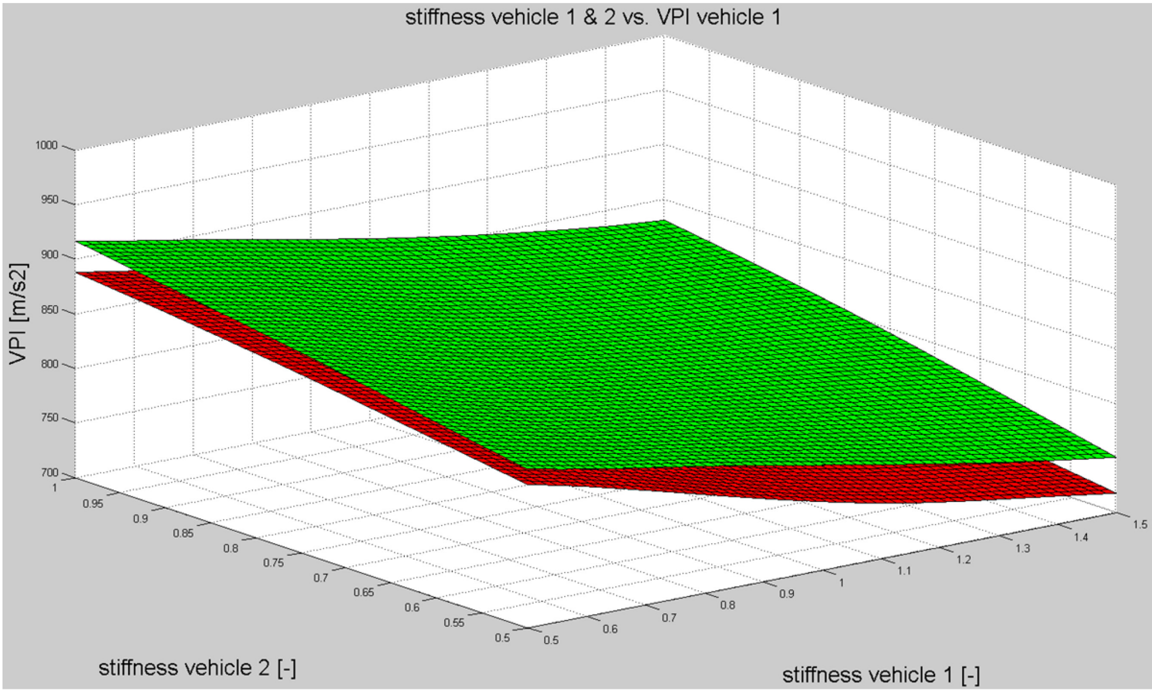

Figure 4.12: VPI of Supermini 2 with connected cross beam (green) and cross beam failure (red).

The simulation of Supermini 2 against default SUV 4 with 50% overlap at 56km/h, with green the connected cross beam and red the failed cross beam with default longitudinal stiffness for both vehicles is shown in Figure 4.13.

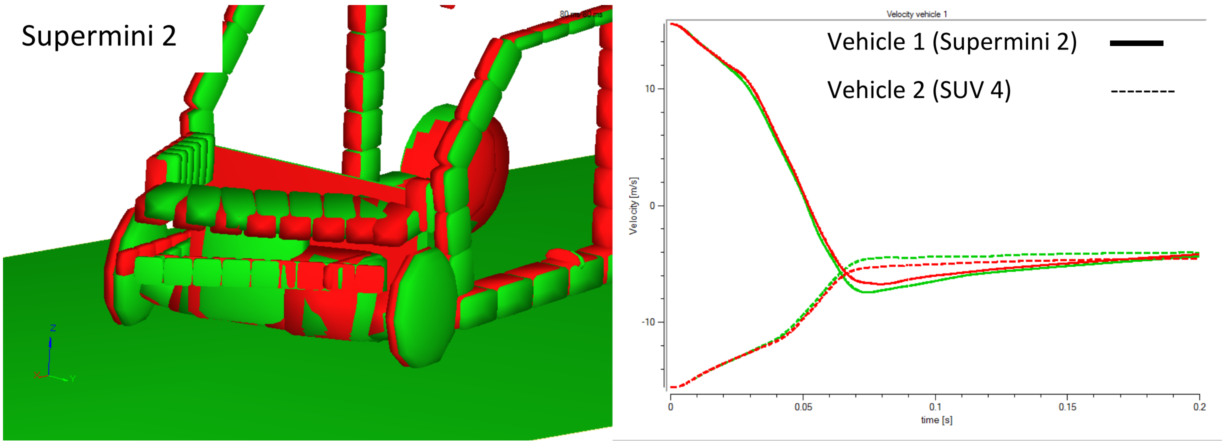

Figure 4.13: Cross beam connected (green) and cross beam failed (red) Supermini 2 - SUV 4.

As observed in fleet study I also fleet study II demonstrates that an impact with a vehicle with cross beam failure gives lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected. However, it needs to be noted that phenomena like intrusion resulting from the cross beam failure are not considered in the simulation. Therefore the VPI might give a wrong estimation of the dummy loadings.

5 CONCLUSION

The objective of this deliverable is to describe a methodology for predicting future vehicle fleet characteristics. The results of the performed fleet studies show that it is possible to evaluate and predict the effect of various vehicle characteristics on the overall crash performance, represented by VPI (Vehicle Pulse Index), of the (future) vehicle fleet.

From the performed fleet studies it can be concluded that:

- A higher vehicle mass results in a lower VPI. For the opponent vehicle an impact with a vehicle with higher mass results in higher VPI.
- An impact with a vehicle that shows cross beam failure shows lower VPI values for both vehicles compared to an impact with a vehicle in which the cross beam stays connected, as this increases the overall stiffness of the vehicle.
- A higher longitudinal stiffness results in a higher VPI, for as well vehicle 1 with stiffer longitudinal, but even more for the opponent vehicle 2.

It should be taken into account that due to the assumptions made in the used MADYMO models some phenomena are not represented that might have an effect on the occupant. Cross beam failure and/or lower longitudinal stiffness result in a vehicle with lower crash stiffness in frontal impacts. This lower stiffness gives a lower VPI value, but in reality it might result in intrusion of the occupant compartment, which was not taken into account in the current vehicle models.

6 GLOSSARY

ASI:	Acceleration Severity Index
Euro NCAP:	European New Car Assessment Programme
FWDB:	Full Width Deformable Barrier
MDB:	Moving Deformable Barrier
ODB:	Off-set Deformable Barrier
SUV:	Sports Utility Vehicle
VC-Compat:	EC funded project (FP5) Vehicle Crash Compatibility
VPI:	Vehicle Pulse Index

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